The Sun's Magnetic Dynamo
Old Clues for New Theories

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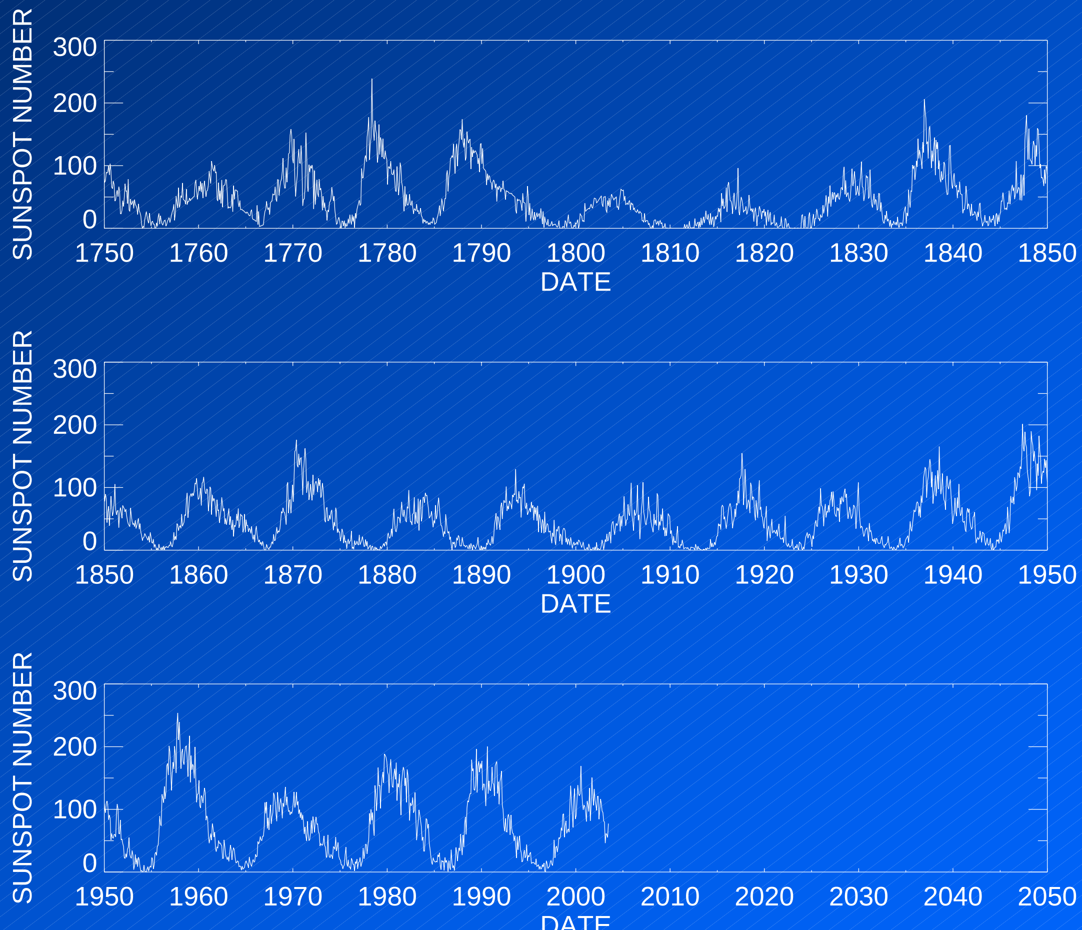
Outline

- Sunspot Cycle Characteristics
- Magnetic Dynamo Models
- The Meridional Circulation
- Latitude Drift of Sunspot Zones
- Conclusions
- Future Research

The "11-year" Sunspot or Wolf Cycle

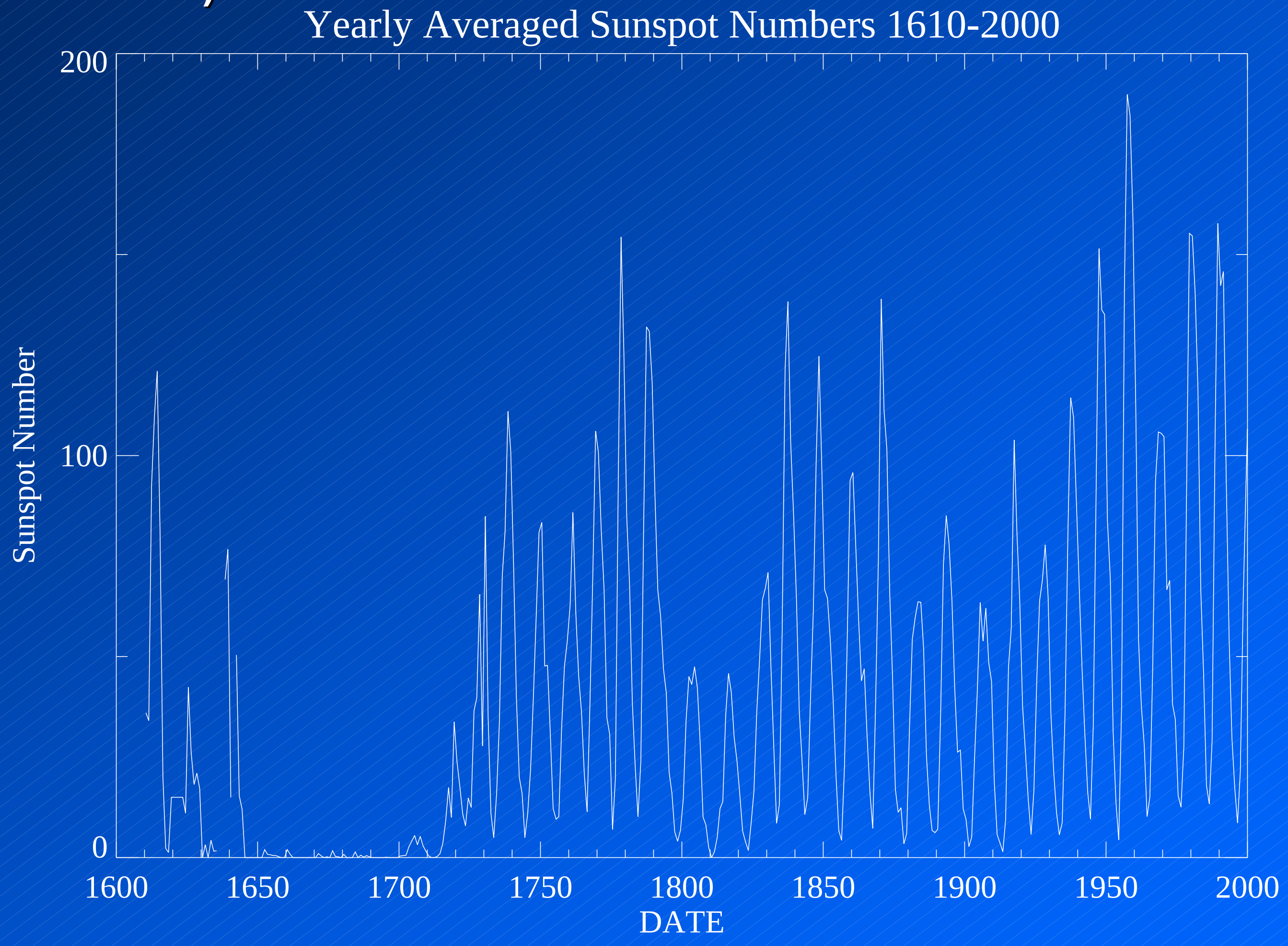
[Schwabe, 1844]

Dynamo models must explain the cycle period and cycle shape (asymmetric with a rapid rise and a slow decline with large cycles rising to maximum in less time than small cycles).



The Maunder Minimum

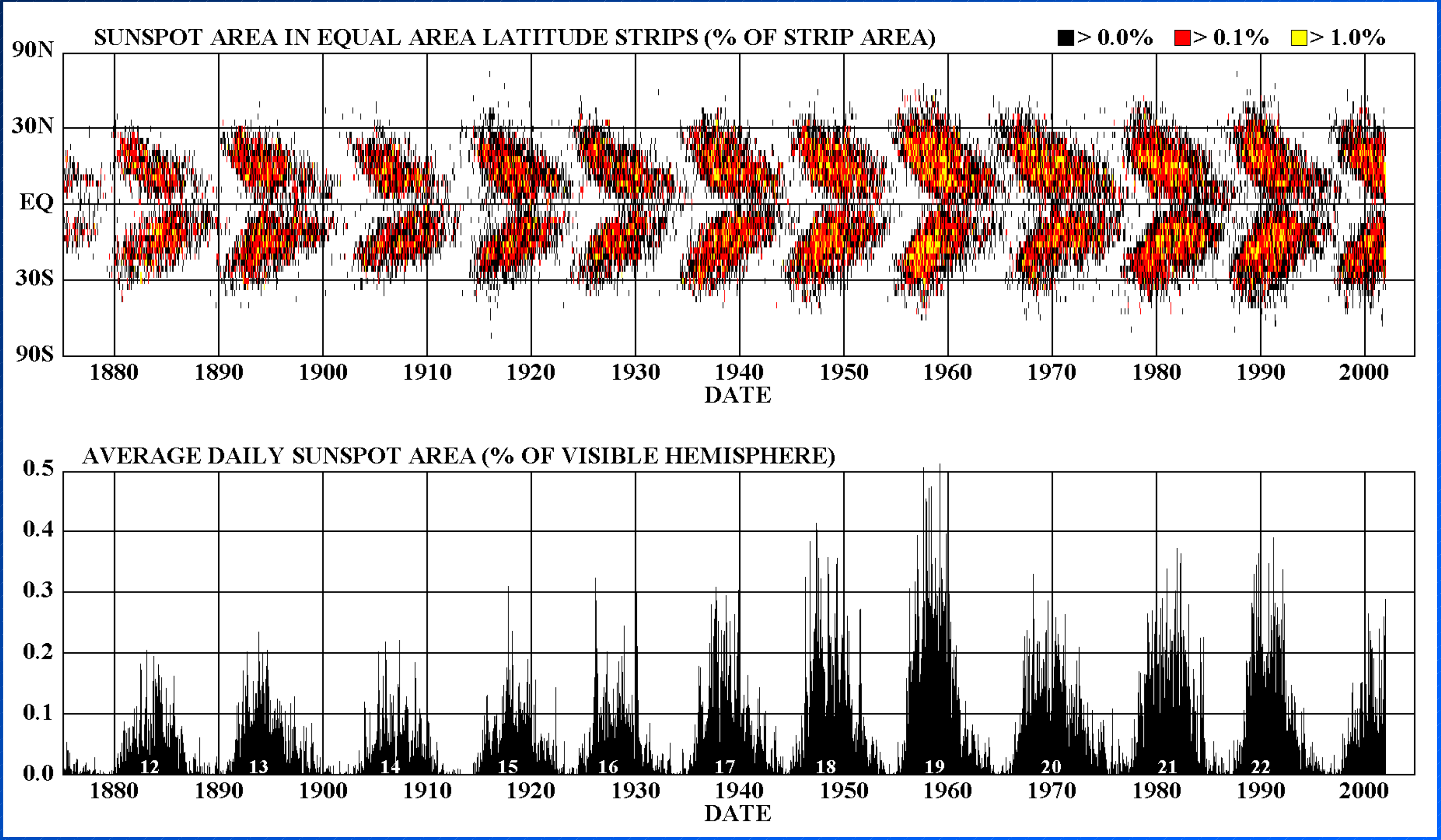
Dynamo models should explain the variability in cycle amplitude and the occurrence of periods of inactivity like the Maunder Minimum (1645-1715).



Sunspot Latitude Drift: Spörer's Law

[Carrington, 1858]

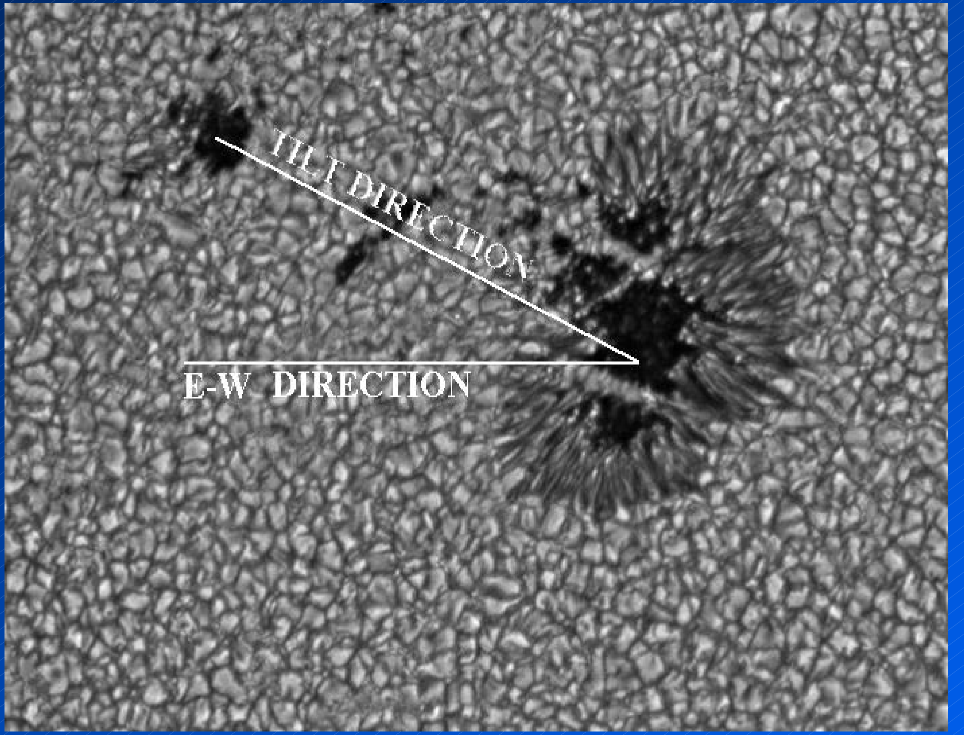
Sunspots appear in two bands on either side of the equator. These bands spread in latitude and then migrate toward the equator as the cycle progresses. Cycles can overlap at the time of minimum.

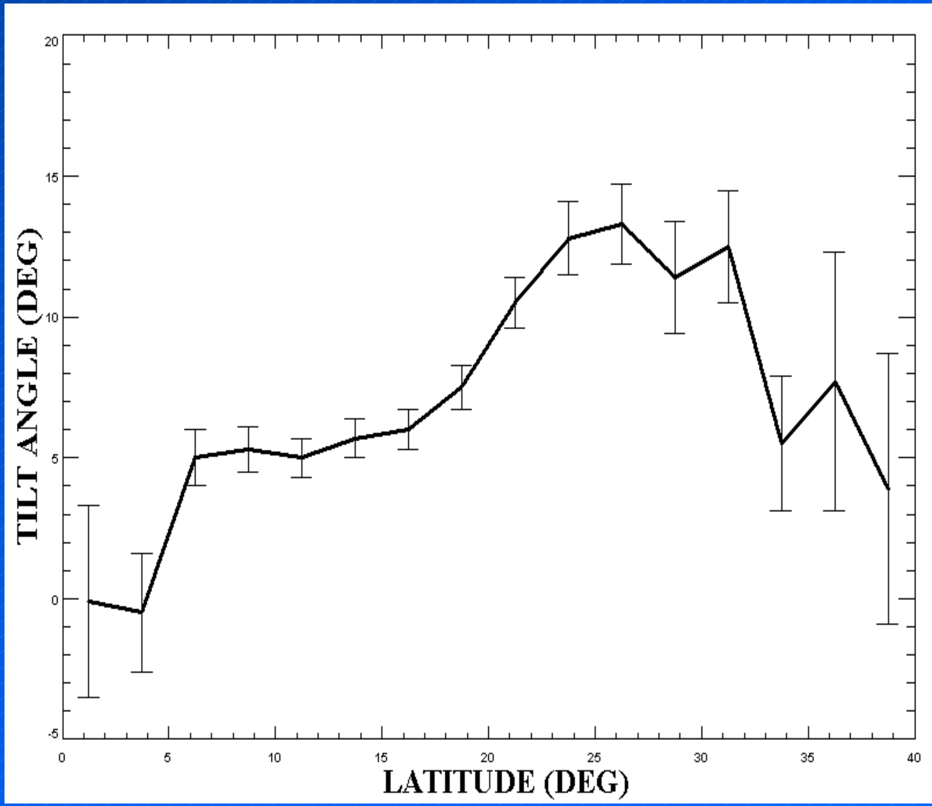


Active Region Tilt: Joy's Law

[Hale *et al.*, 1919]

Active regions are tilted so that the following polarity spots are slightly poleward of the preceding polarity spots. This tilt increases with latitude.

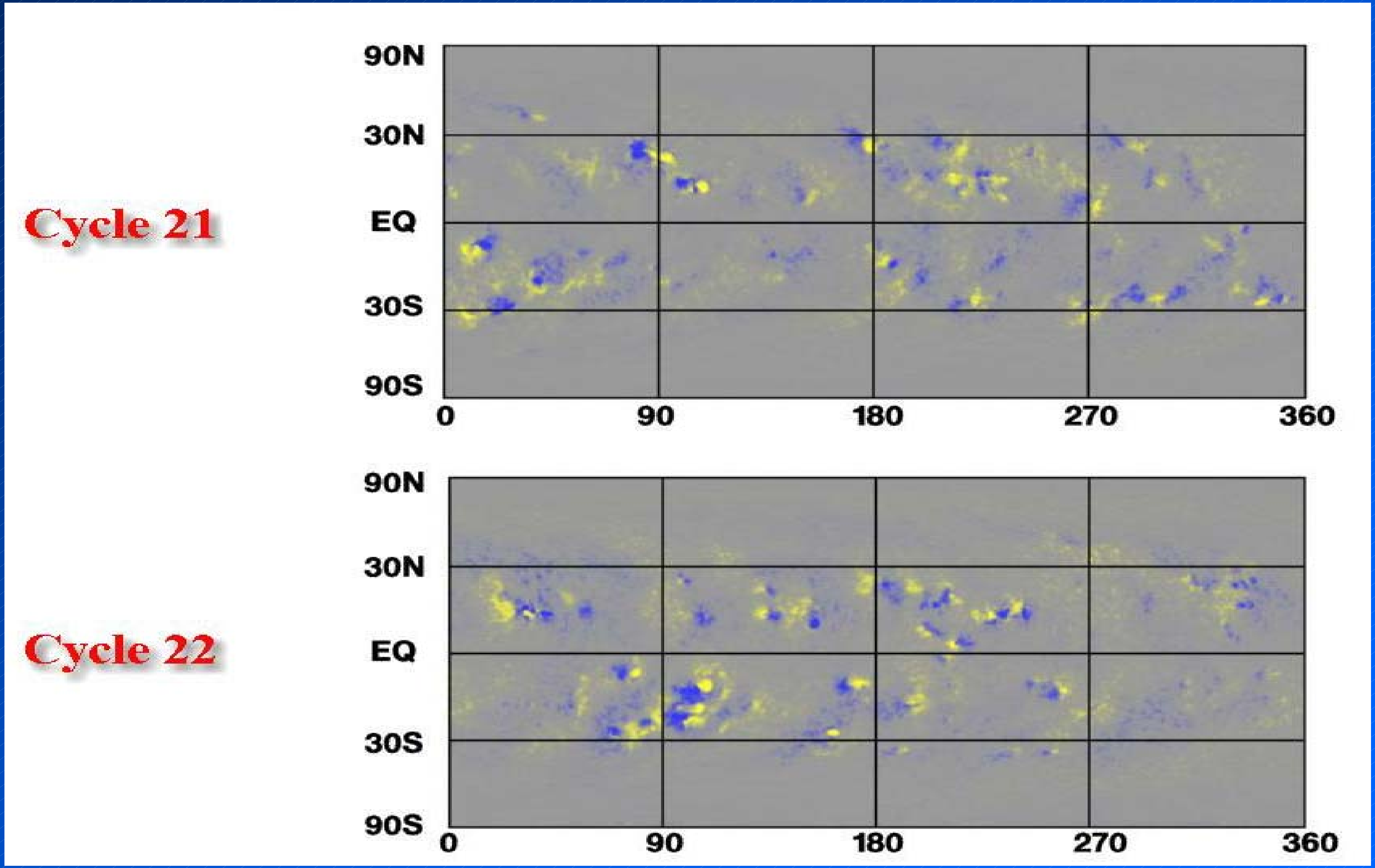




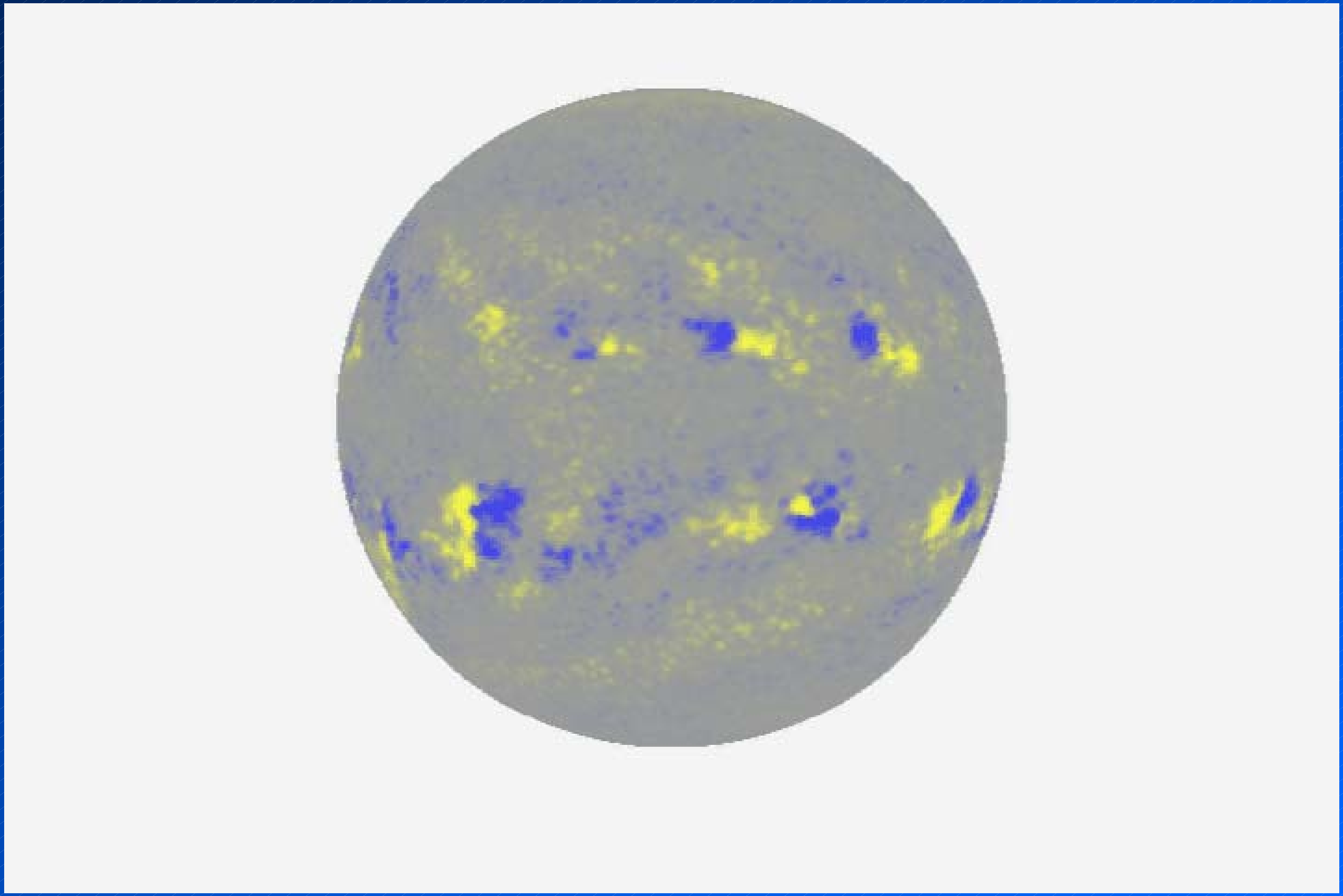
Hale's Polarity Law

[Hale, 1924]

The polarity of the preceding spots in the northern hemisphere is opposite to the polarity of the preceding spots in the southern hemisphere. The polarities reverse from one cycle to the next.



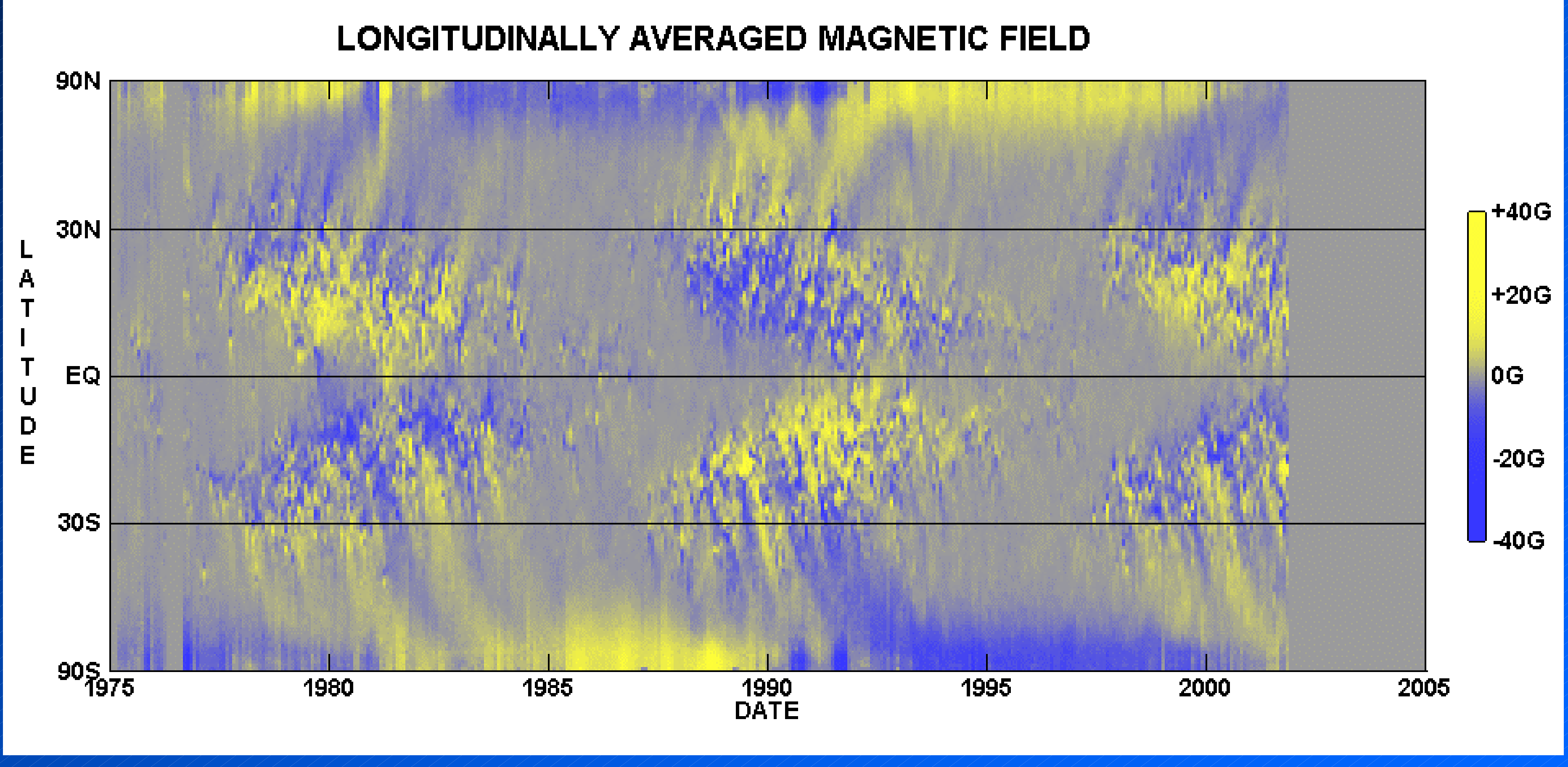
The Sun's Magnetic Cycle



Polar Field Reversal at Cycle Maximum

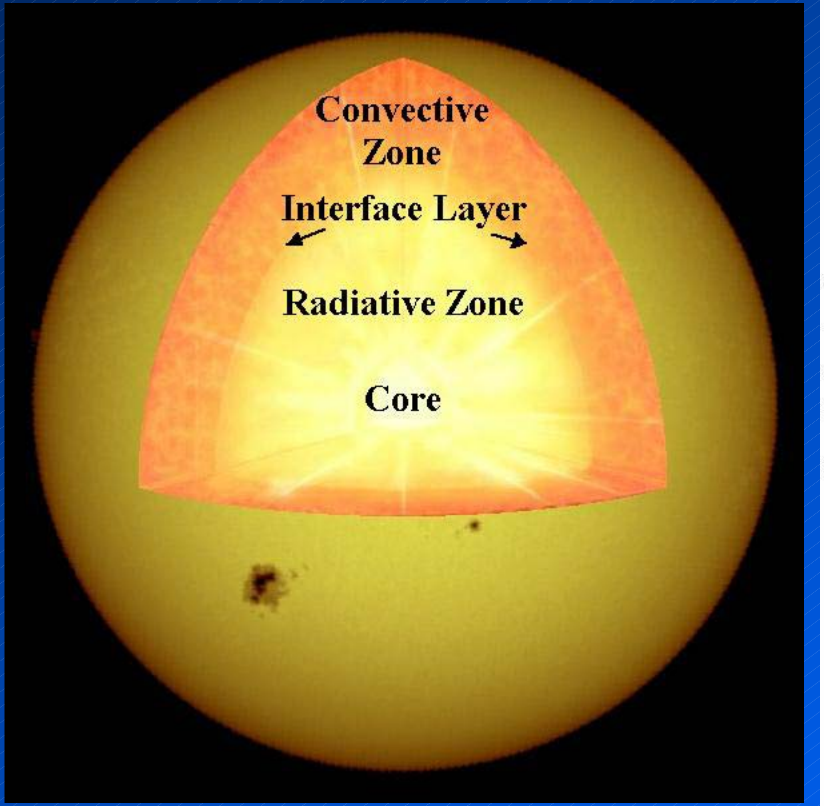
[Babcock, 1959]

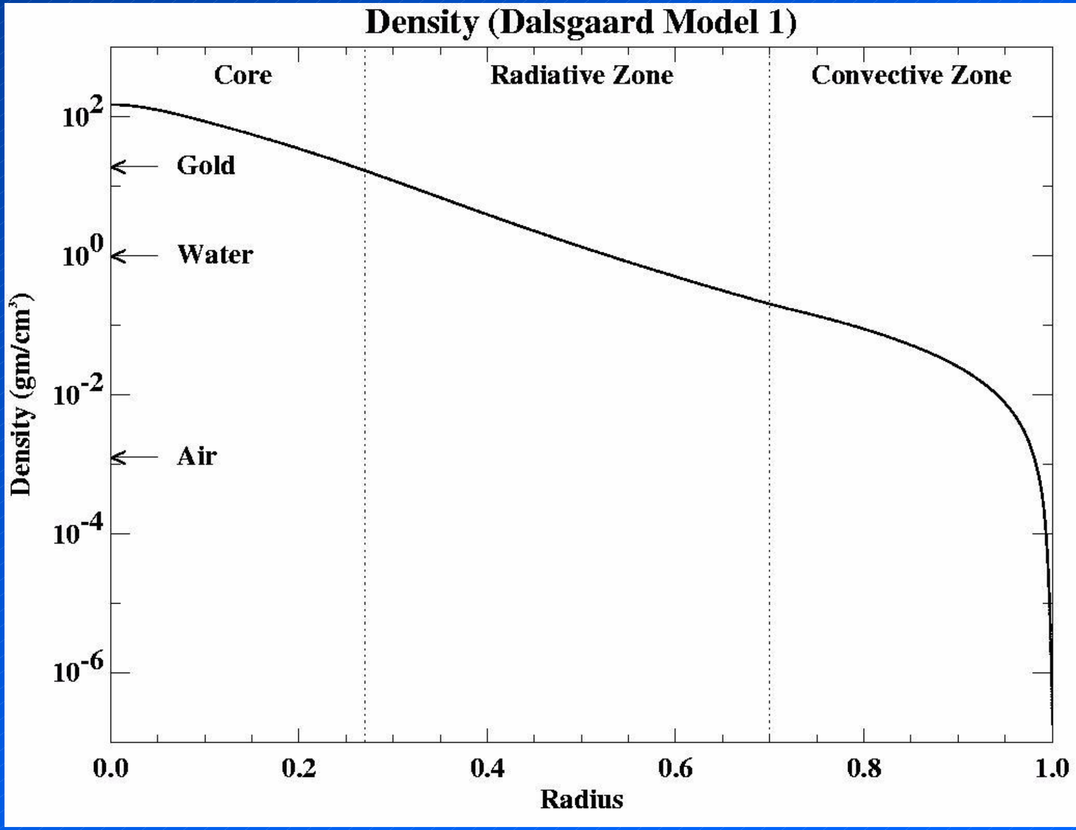
The polarity of the polar magnetic fields reverses at about the time of the solar activity maximum. (Result of Joy's Law + Hale's Law + Meridional Flow + Flux Cancellation across the equator?)



The Solar Interior

Flows within the convection zone were thought to be the source of the solar cycle. Energy is generated in the core and transported by radiation outward through the core and the r5adiative zone. At about 70% of the way to the surface the temperature drops from 15MK to 2MK and metals start to recombine – increasing the opacity. Boiling convective motions carry the energy the rest of the way to the surface.

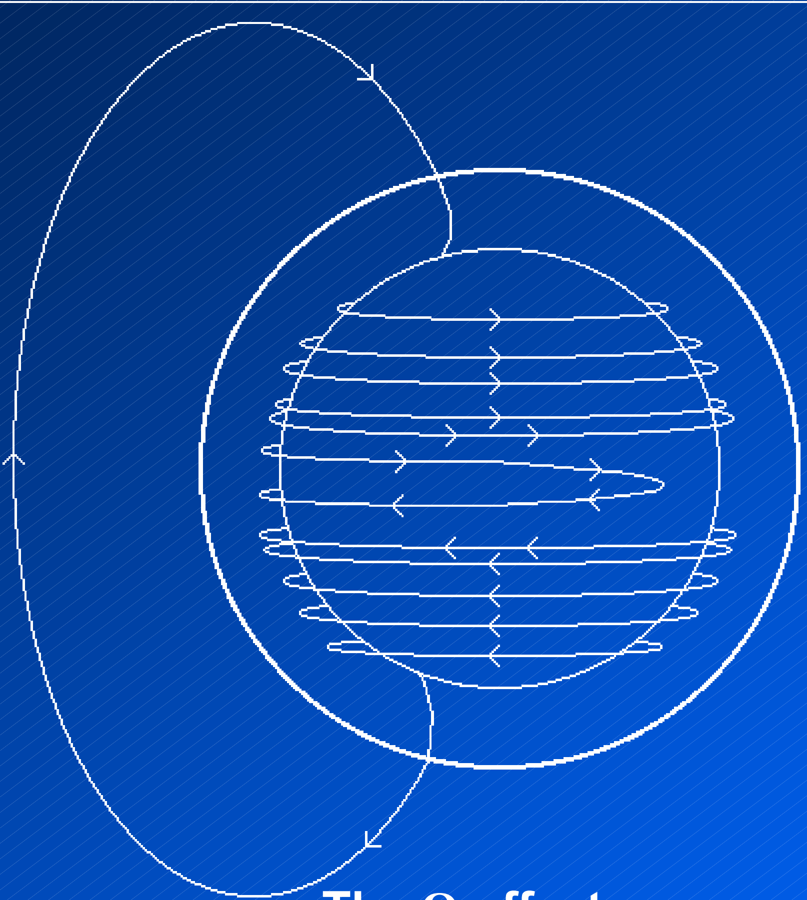




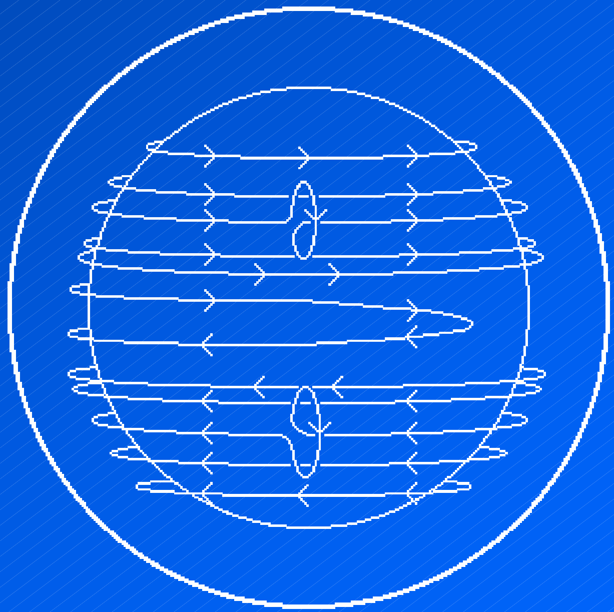
Basic Magnetic Dynamo Processes

Differential rotation in radius and latitude amplifies the poloidal field by wrapping it around the Sun to produce a strong toroidal field.

Lifting and twisting the toroidal field can produce a poloidal field with the opposite orientation.



The Ω-effect

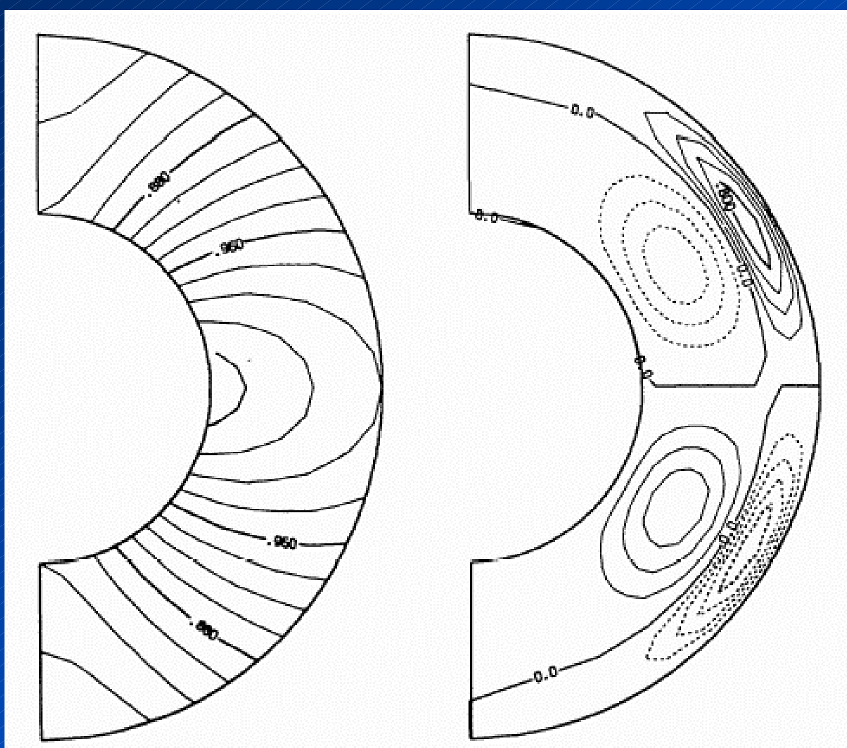


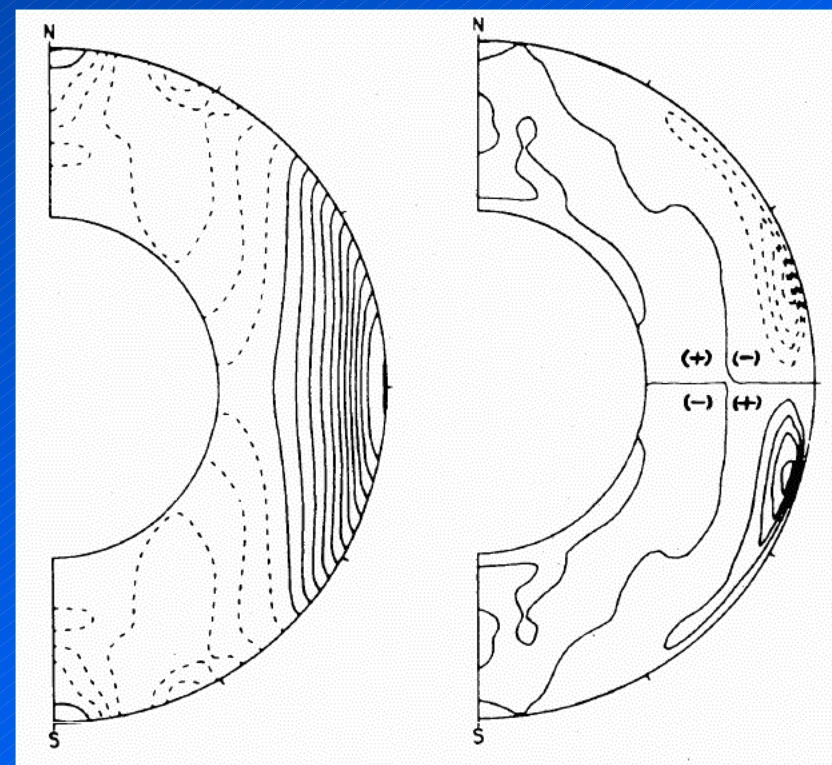
The α-effect

Early Dynamo Models

Kinematic dynamo models assumed internal profiles for both rotation (Ω) and helicity (α) but could produce 11-year cycles with equatorward propagation of activity (Yoshimura, 1975).

MHD dynamo models produce internal profiles for both rotation (Ω) and helicity (α) but produce short cycles cycles with poleward propagation of activity (Glatzmaier, 1985).



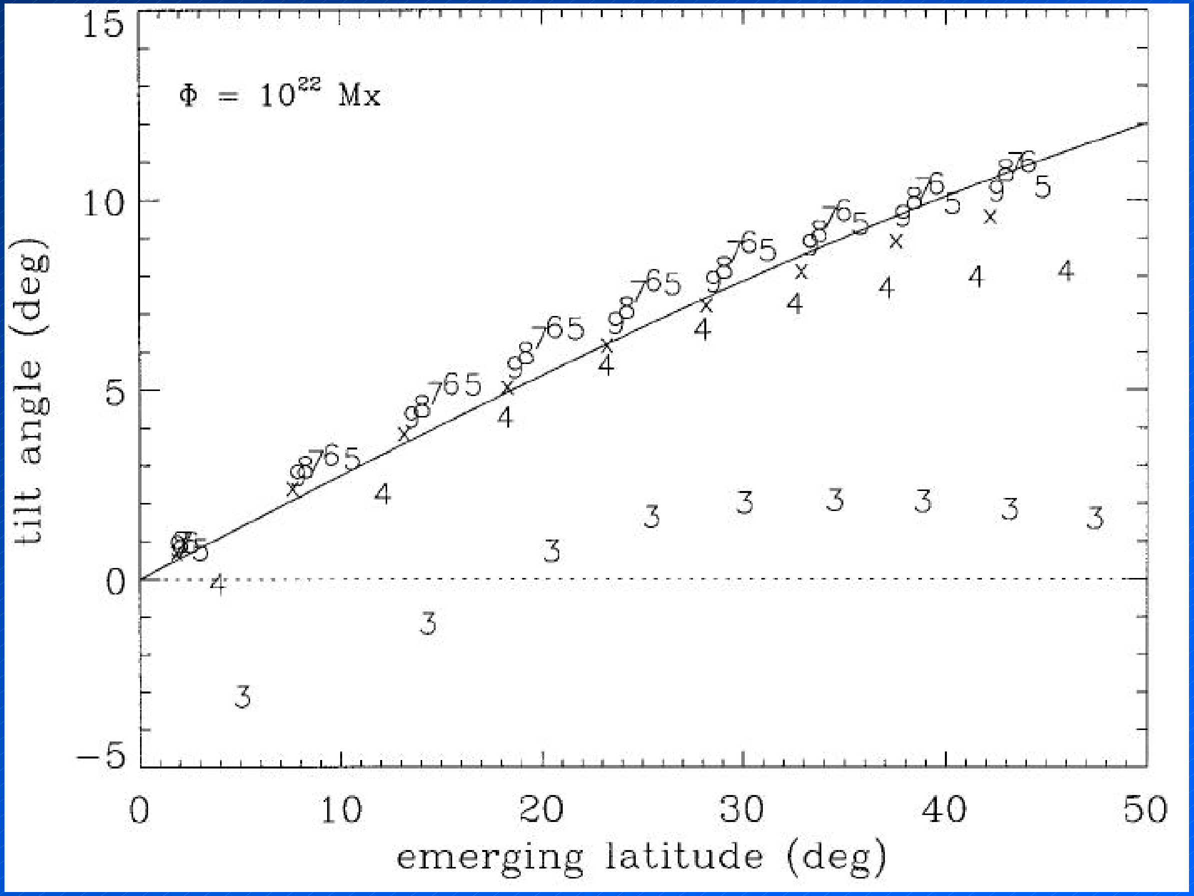


Fatal Flaws in the Dynamos

Flows within the convection zone were previously thought to be the source of the solar cycle (for both α- and Ω-effects). Both dynamo types had a problem with too much α-effect in the convection zone. Now, important aspects of convection zone rotation and flux tube dynamics indicate that the interface layer or "tachocline" is the seat of the solar cycle and both of the early models were fatally flawed.

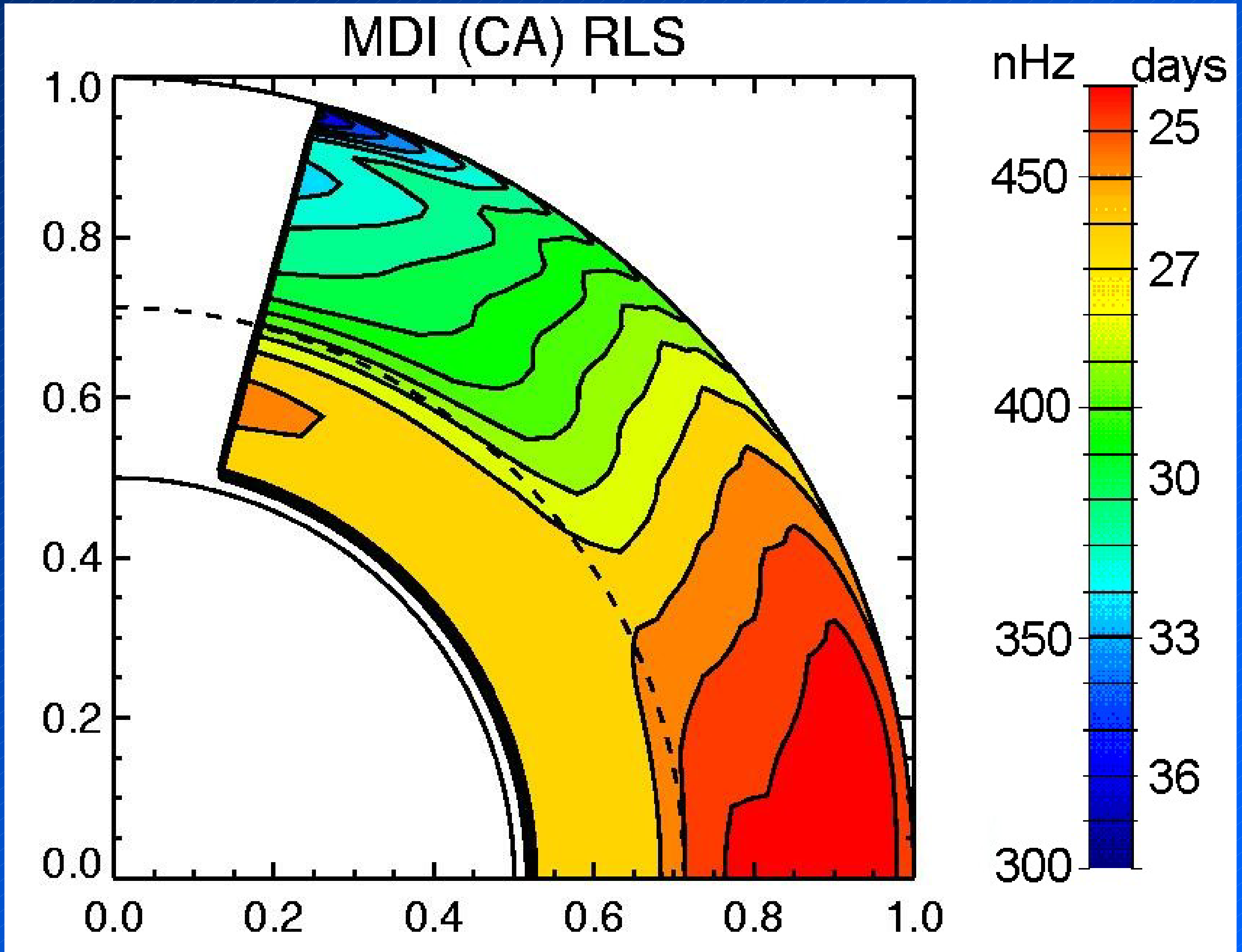
Dynamics of Buoyant Magnetic Flux

Flux tubes rise ***rapidly*** from the tachocline, move to slightly higher latitudes (where the rotation rate is slower), are twisted slightly by the Coriolis force (as in Joy's Law), and produce asymmetries between the preceeding and following legs as they emerge through the photosphere (Fan and Fisher 1996).



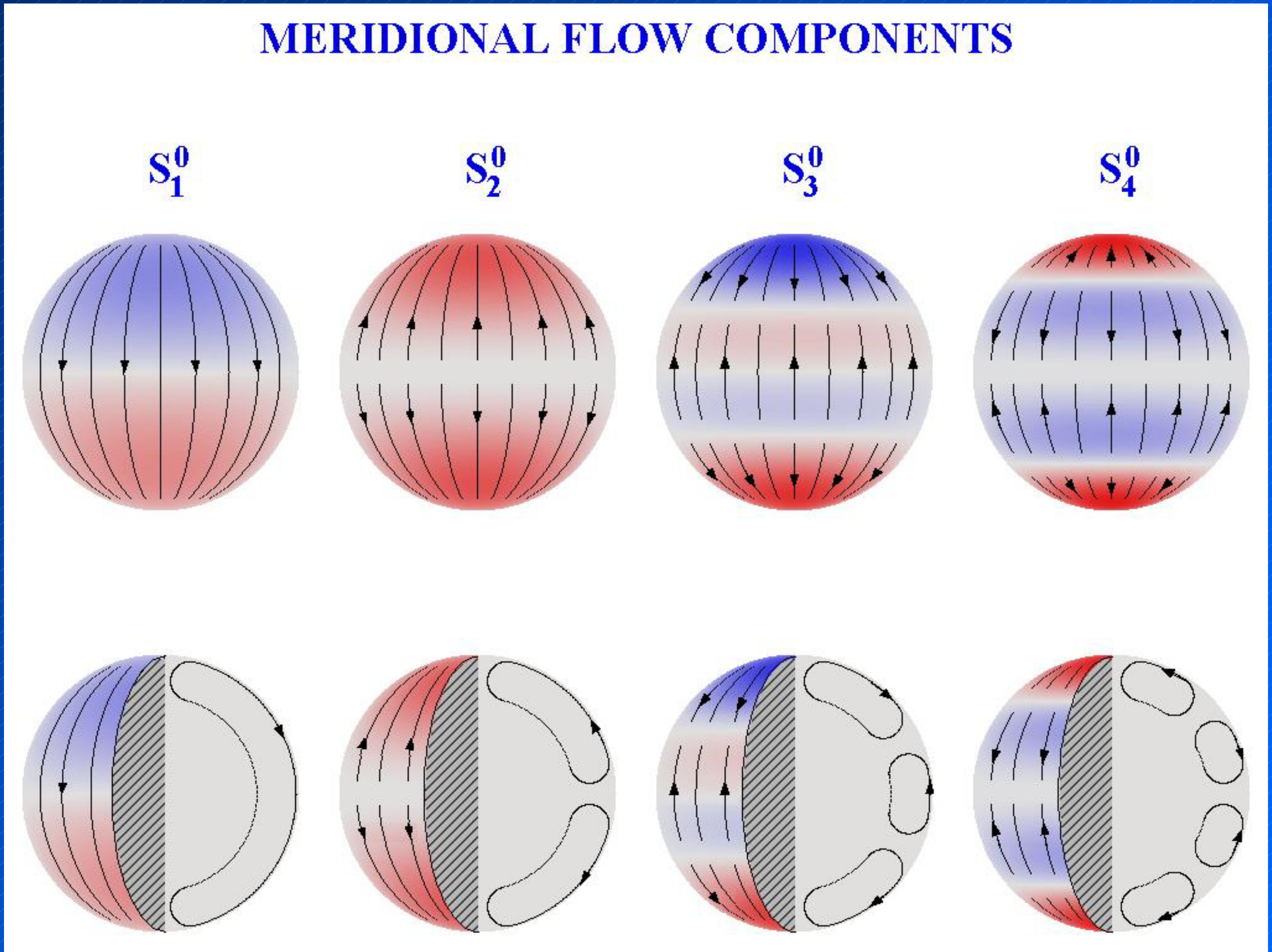
Internal Rotation Rate

Helioseismic determinations of the internal rotation rate show that the latitudinal differential rotation seen at the surface extends through the convection zone. Layers of strong radial shear are found near the surface and at the base of the convection zone (the tachocline). *<u>This is different than what was assumed and produced in the earlier dynamos.</u>*



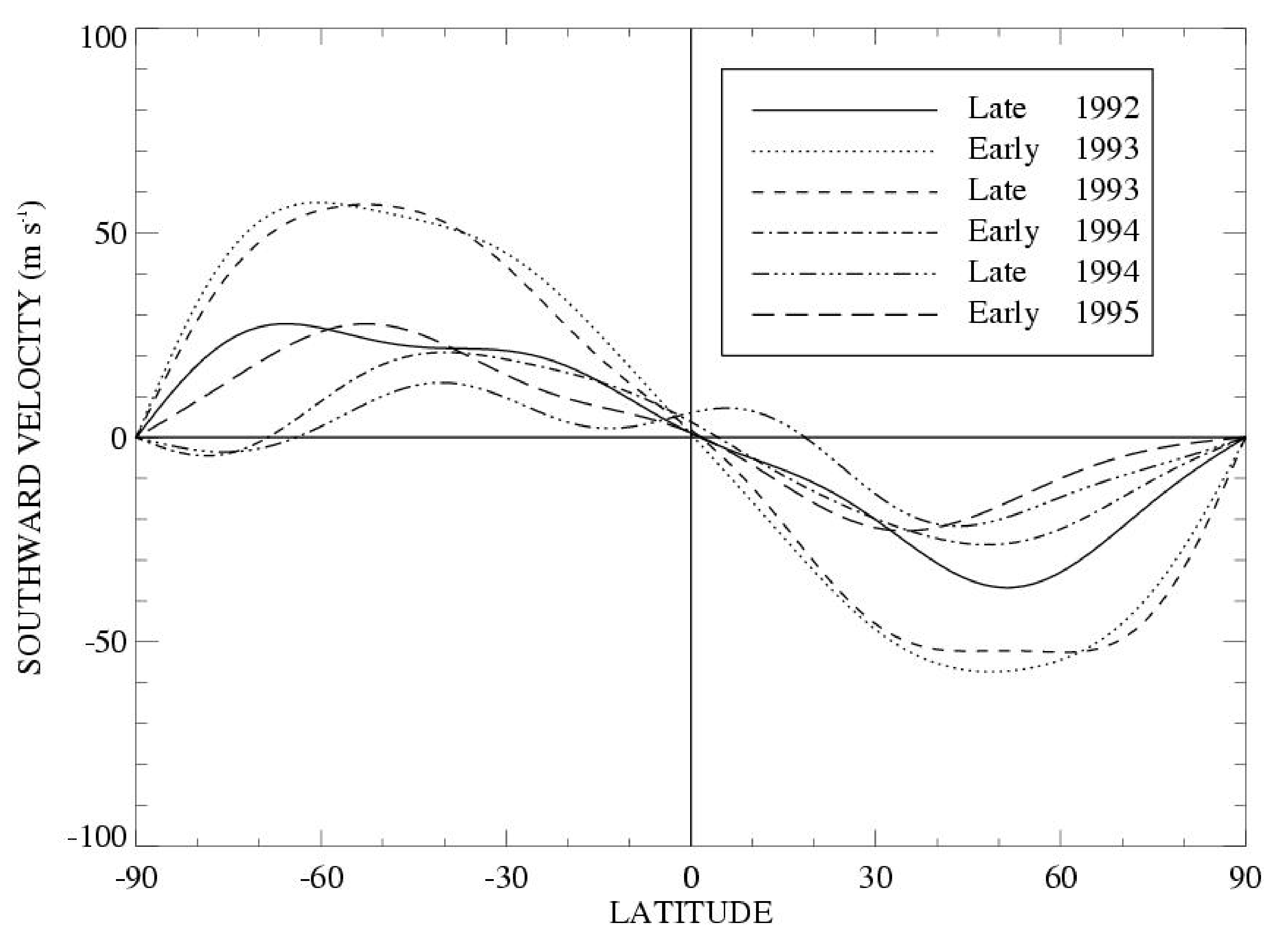
The Meridional Circulation – an Added Ingredient

Hathaway (ApJ 1996) developed an image analysis technique for extracting the signal due to the meridional flow from Doppler velocity images. The meridional flow is largely poleward at ~20 m/s but variable.



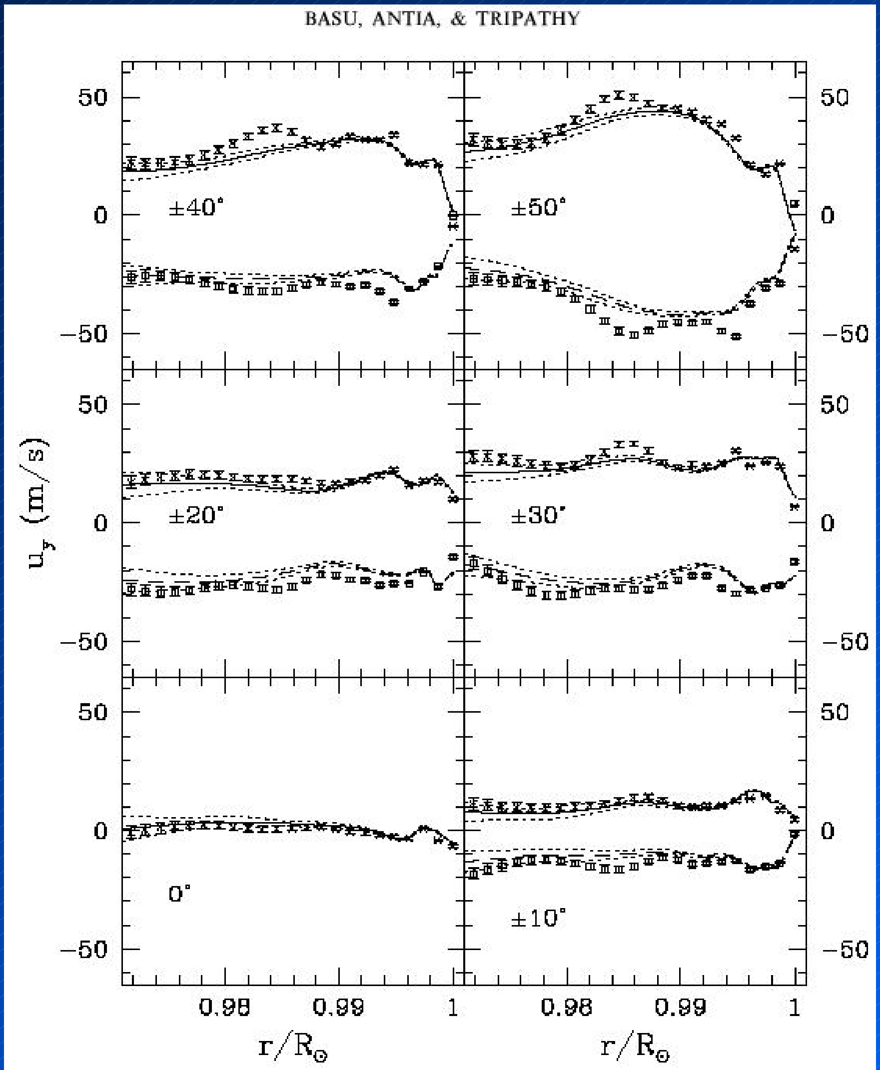
The Photospheric Meridional Circulation

At and near the surface the flow is largely poleward with a peak velocity of about 20 m/s. There is continuing evidence that the strength and structure of the flow is time-dependent.

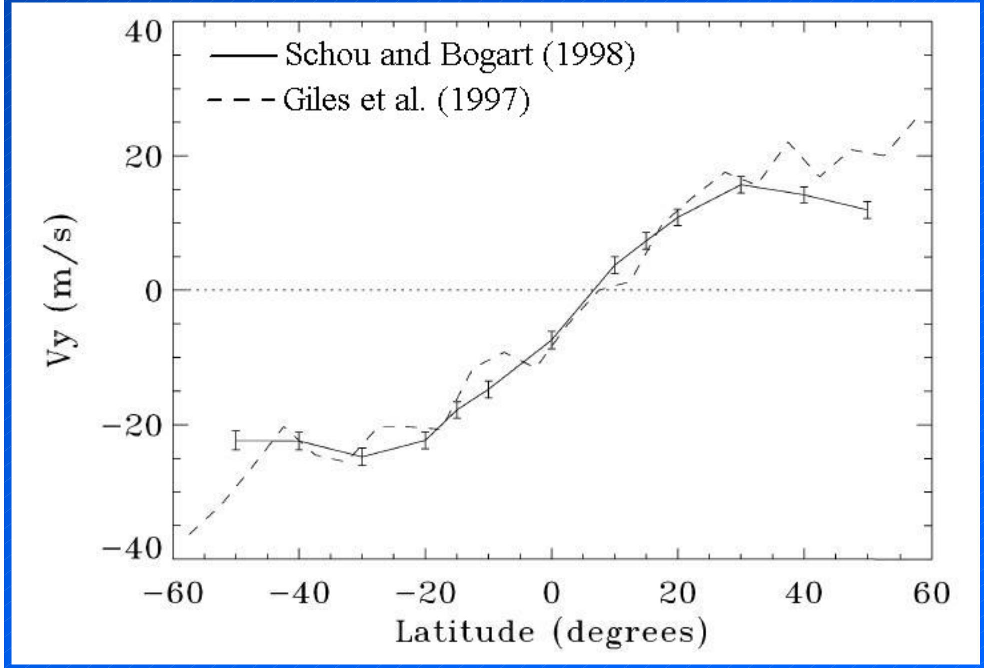


The Interior Meridional Circulation

Local Helioseismology has recently revealed aspects of the internal structure of the Meridional Circulation. (Giles et al., 1997; Braun and Fan, 1998; Schou and Bogart, 1998; Basu, Antia, and Tripathy 1999)

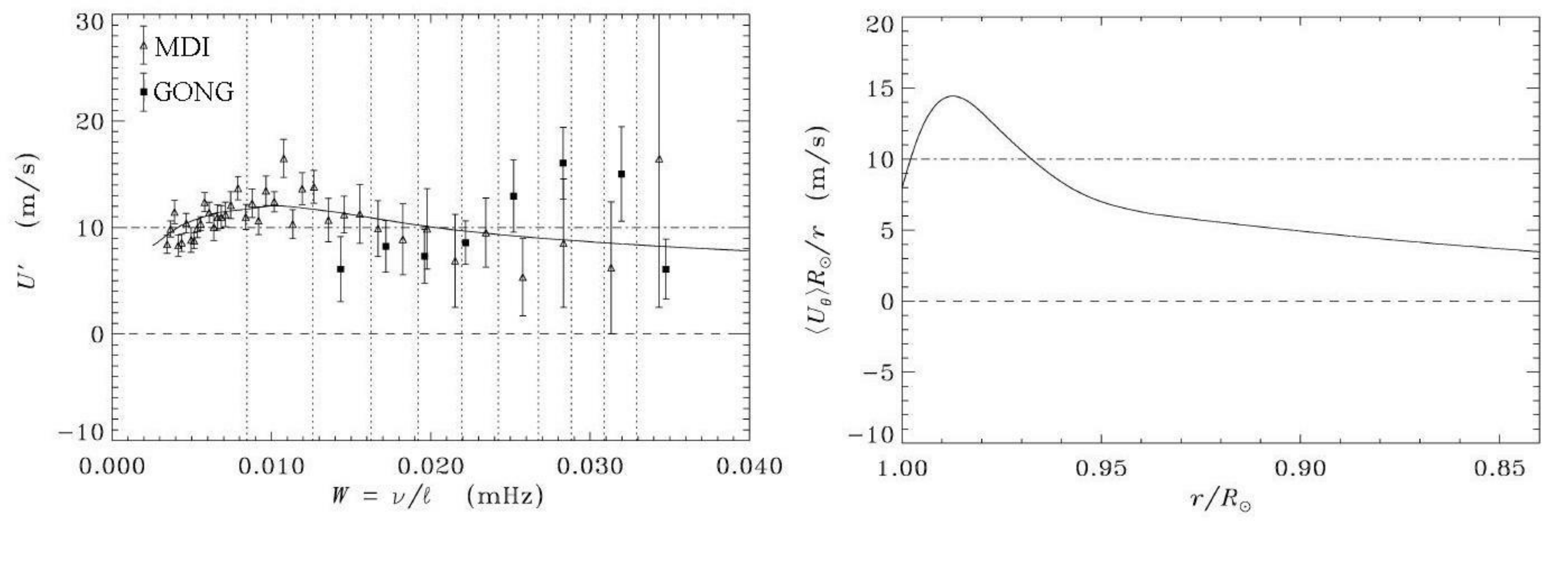


All of these investigations indicate a poleward meridional flow of about 20 m/s that persists with depth.

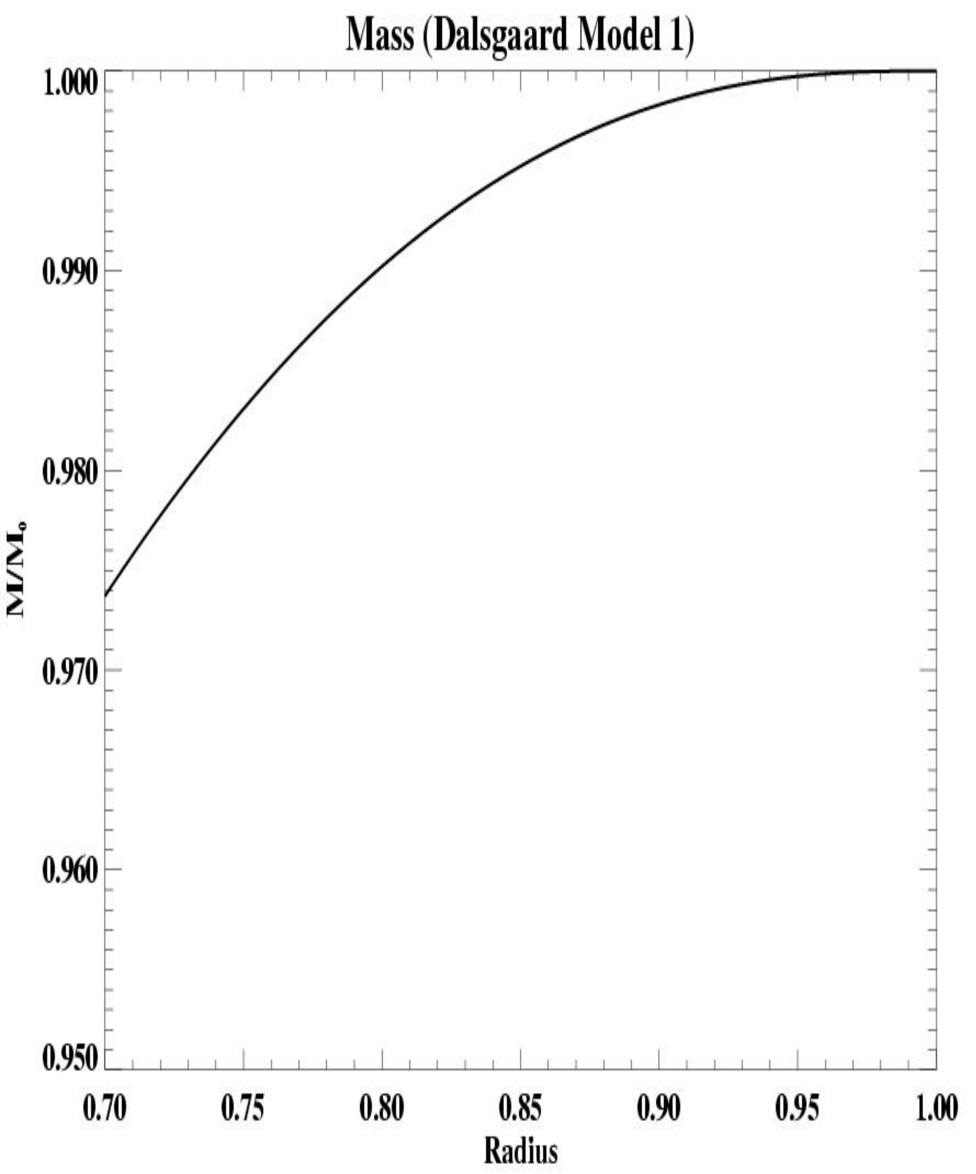


“Deep” Interior Meridional Circulation

Braun and Fan (1998) found that the poleward flow extends at least 10 to 15% into the solar interior (30 to 50% through the convection zone). By mass conservation there must be a return flow deeper in, but probably still within the convection zone.



The Meridional Circulation Return Flow



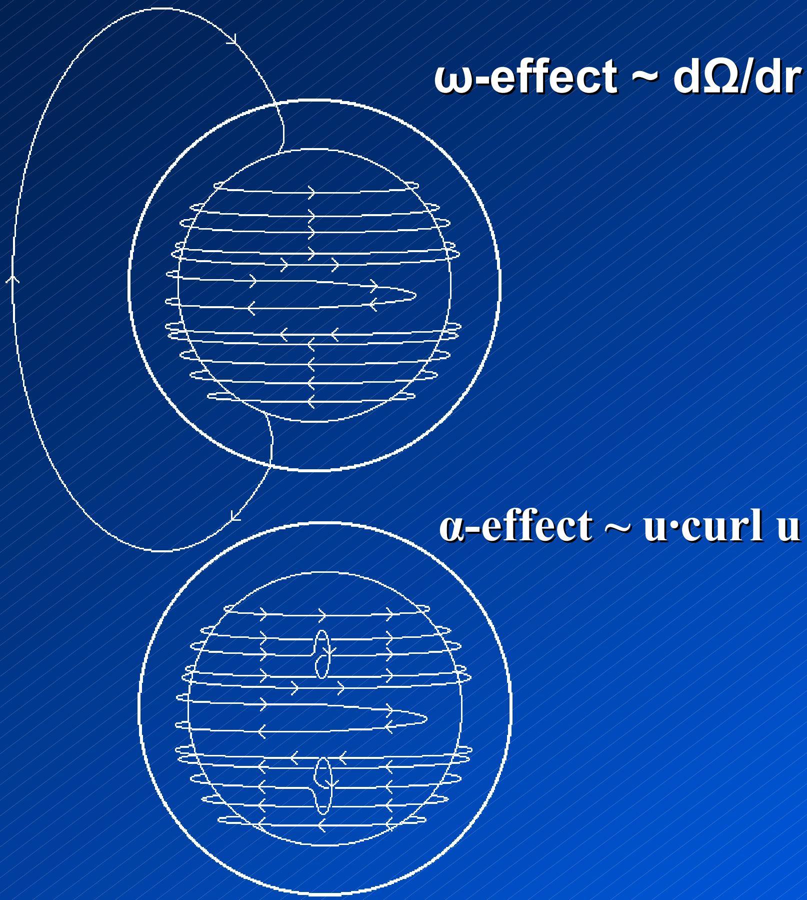
The top half of the CZ contains 0.5% of the Sun's mass. The rest of the CZ contains over 2.5% or 5 times as much mass.

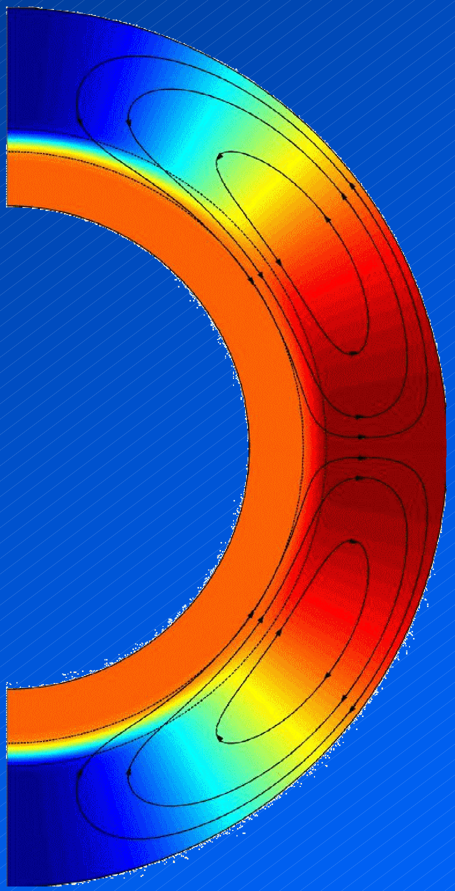
A poleward flow of 10 m/s in the outer half of the CZ requires an average equatorward flow of just 2 m/s in the lower half.

A 2 m/s flow would carry magnetic flux from the middle latitudes to the equator in about 10 years!

It is important to measure the meridional flow at the base of the convection zone.

Dynamo Wave Vs. Meridional Flow

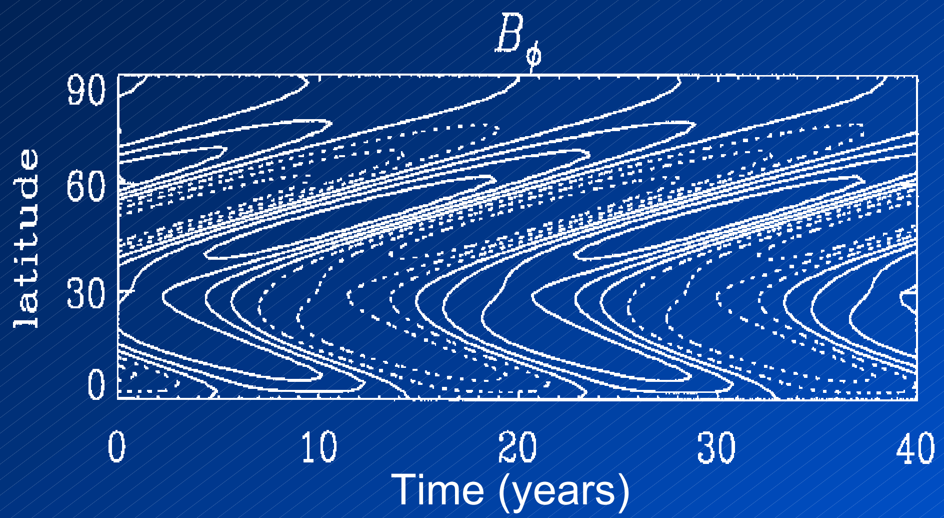




Dynamo waves travel along surfaces of constant angular velocity in a direction determined by the sign of $\alpha \cdot \omega$ and a period ~ $1/\sqrt{\alpha\omega}$

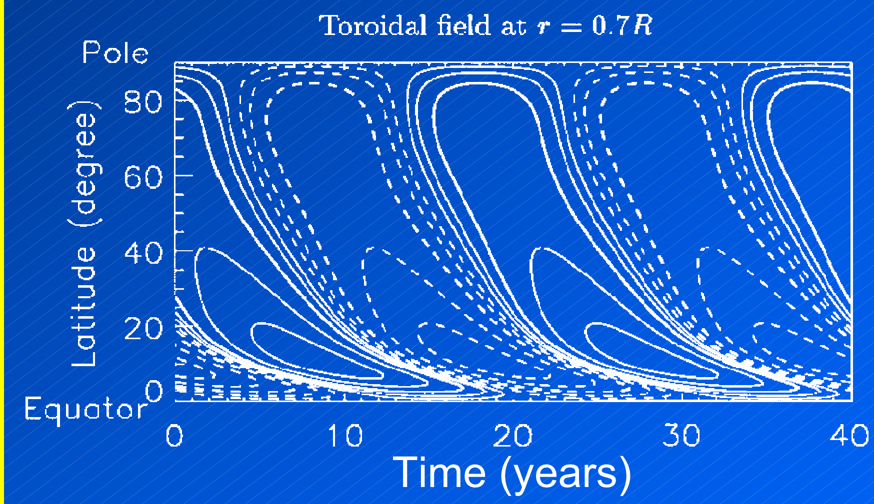
With meridional flow the activity moves in the flow direction with period ~ 1/Velocity

Dynamo Wave Vs. Meridional Flow Butterfly Diagrams



Rüdiger & Brandenberg (1995)

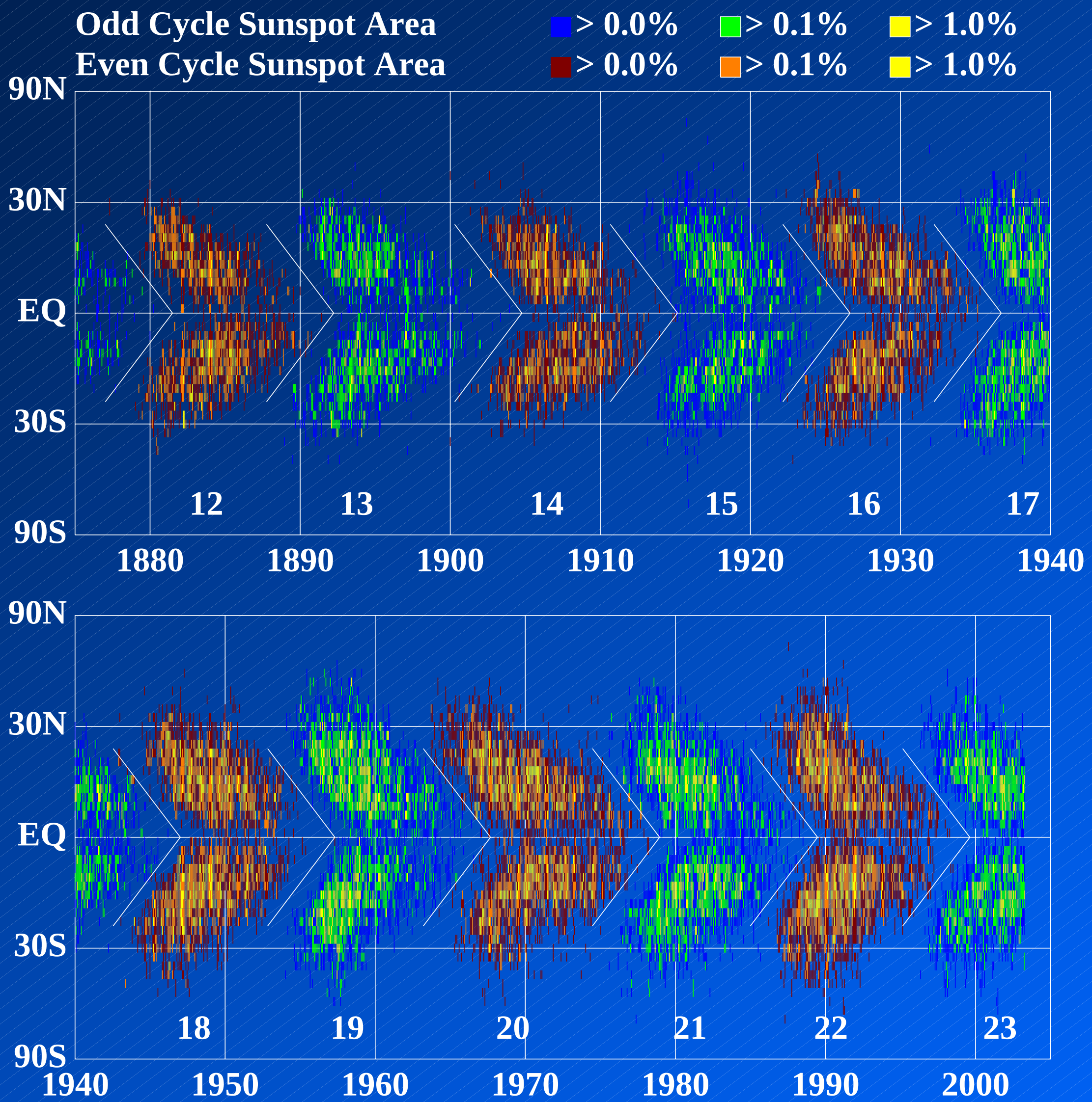
Dynamo wave solutions have a poleward moving branch at high latitudes and drift rates that are nearly constant with latitude.



Dikpati & Charbonneau (1999)

Solutions with meridional flow do not have the poleward moving branch and have drift rates that are slower nearer the equator.

Latitude Drift of Sunspot Zones

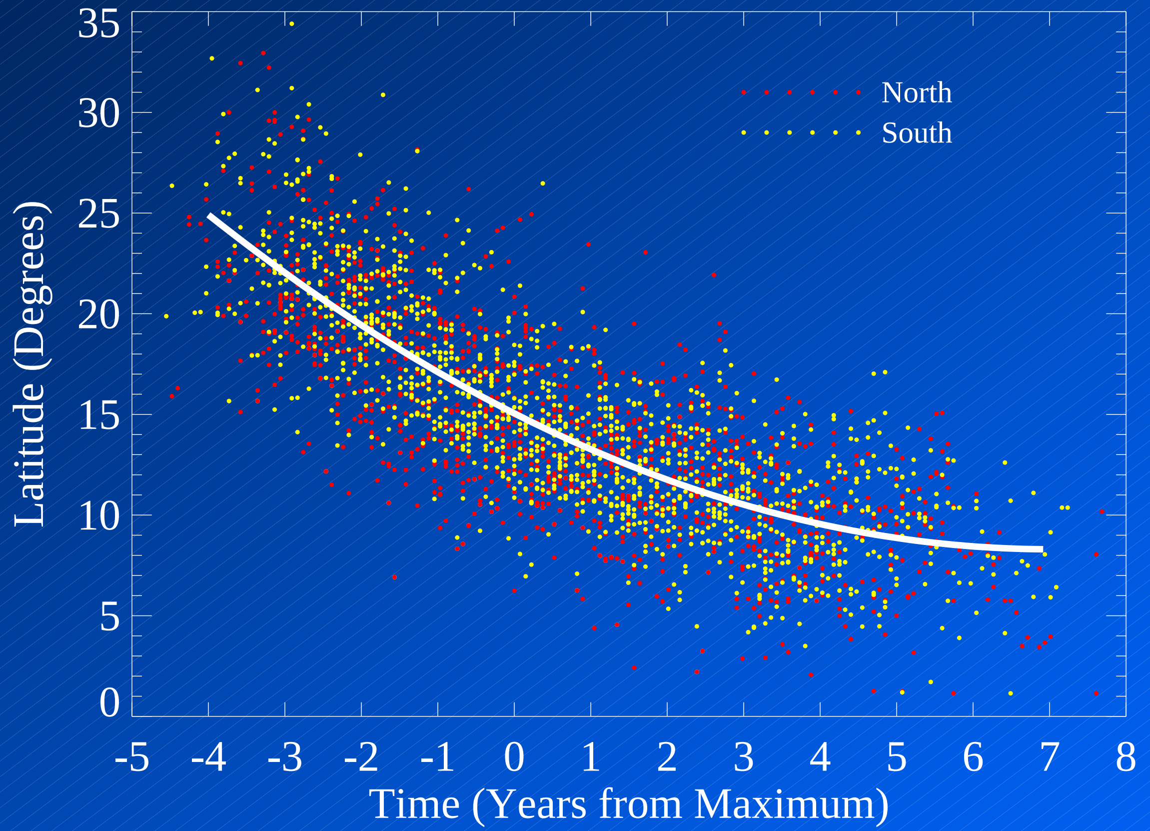


We examined the latitude drift of the sunspot zones by first separating the cycles where they overlap at minimum.

We then calculated the centroid position of the daily sunspot area averaged over solar rotations for each hemisphere.

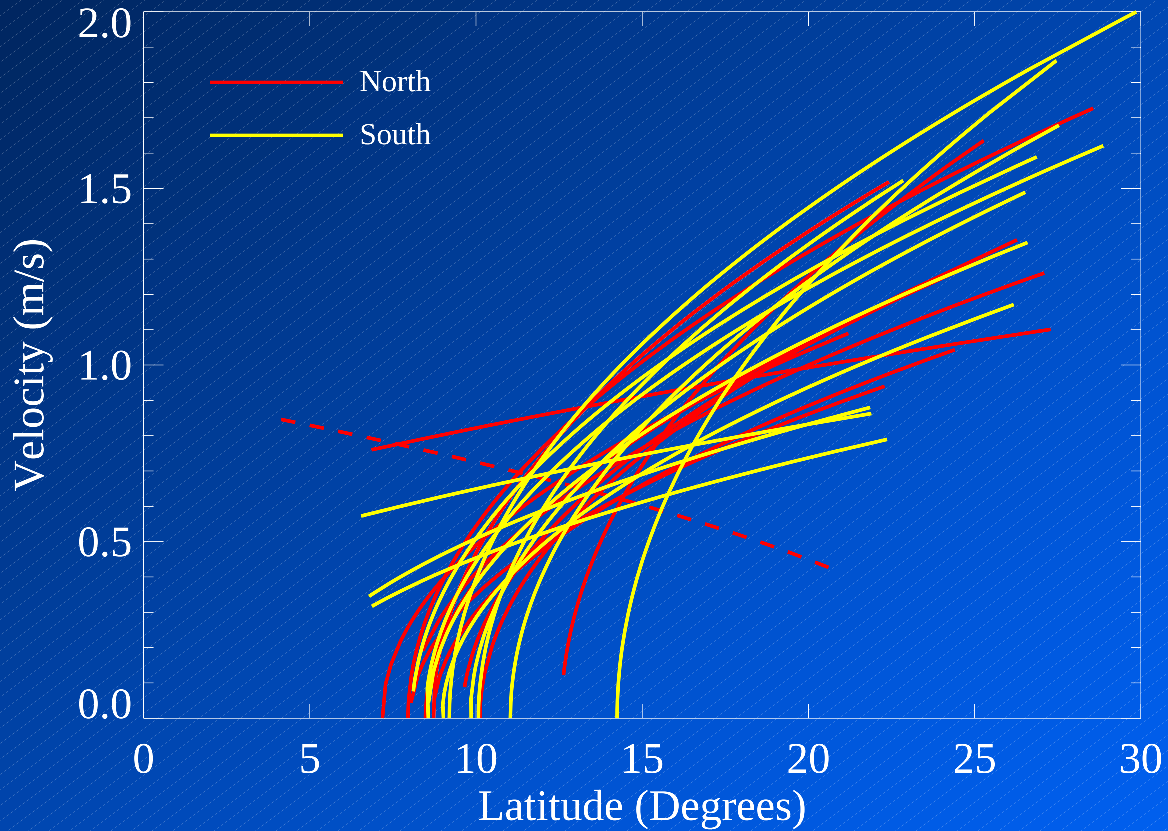
[Hathaway, Nandy, Wilson, & Reichmann, ApJ 2003]

Centroid Position vs. Time



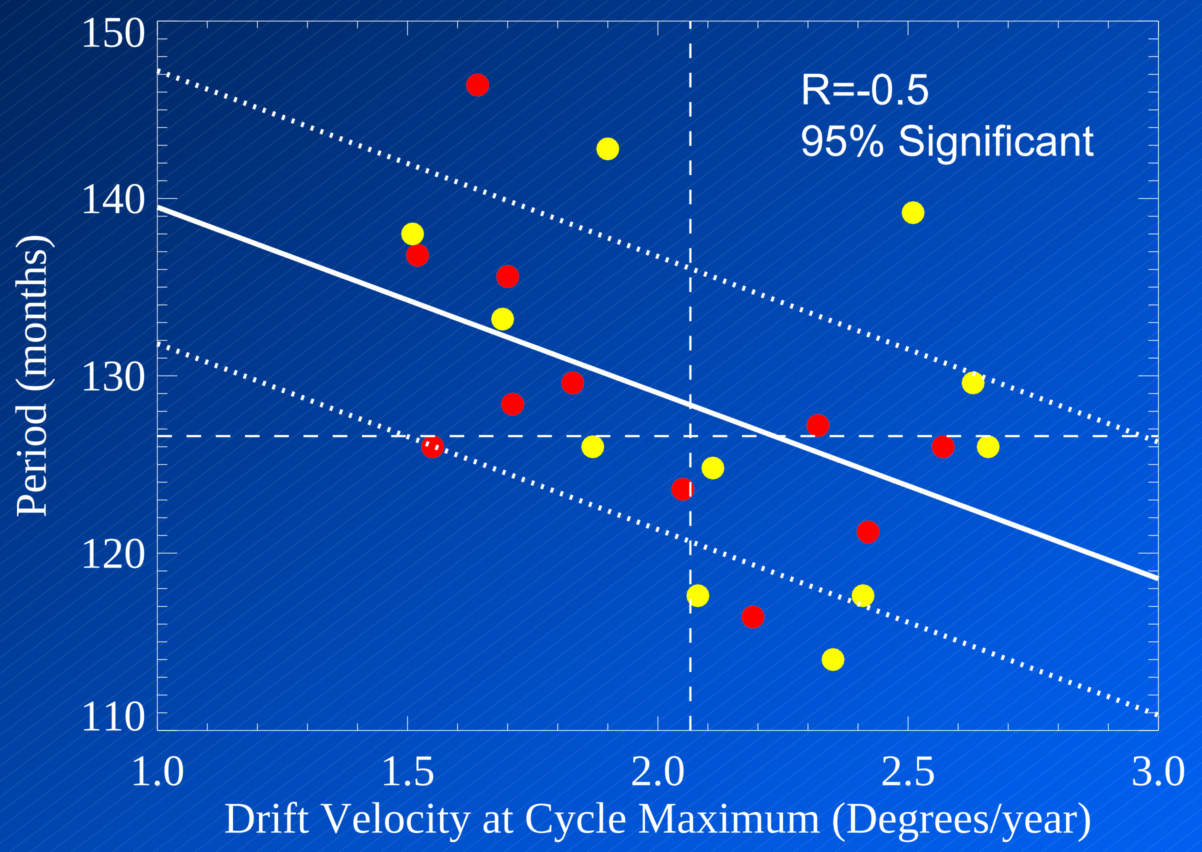
The centroid of the sunspot area drifts toward the equator and slows to a stop at a latitude of about 8°. The sunspots do not show evidence for the poleward branch at higher latitudes expected from dynamo waves.

Drift Rate vs. Latitude



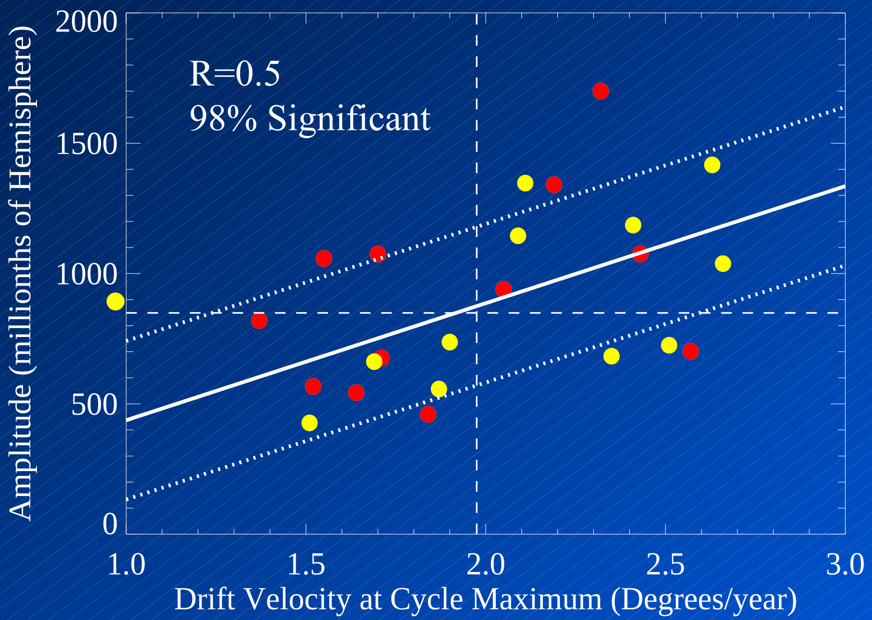
The drift rate in each hemisphere and for each cycle (with one exception) slows as the activity approaches the equator. This behavior follows naturally from the characteristics of a deep meridional flow. The flow amplitude (1-2 m/s) is consistent with helioseismology (Giles, 2000).

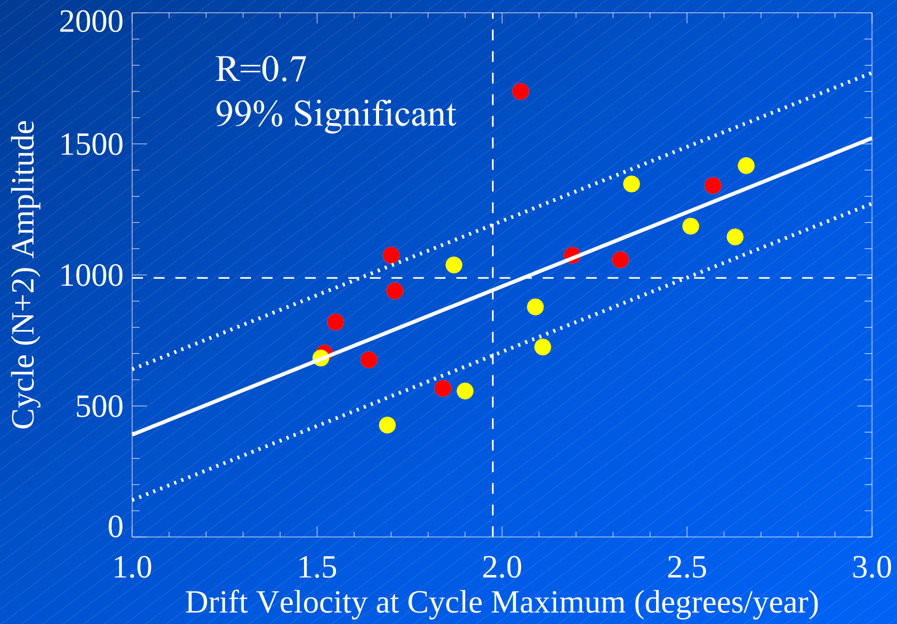
Drift Rate – Period Anti-correlation



The sunspot cycle period is anti-correlated with the drift velocity at cycle maximum. The faster the drift rate the shorter the period. This is precisely what is predicted by dynamo models with deep meridional flow.

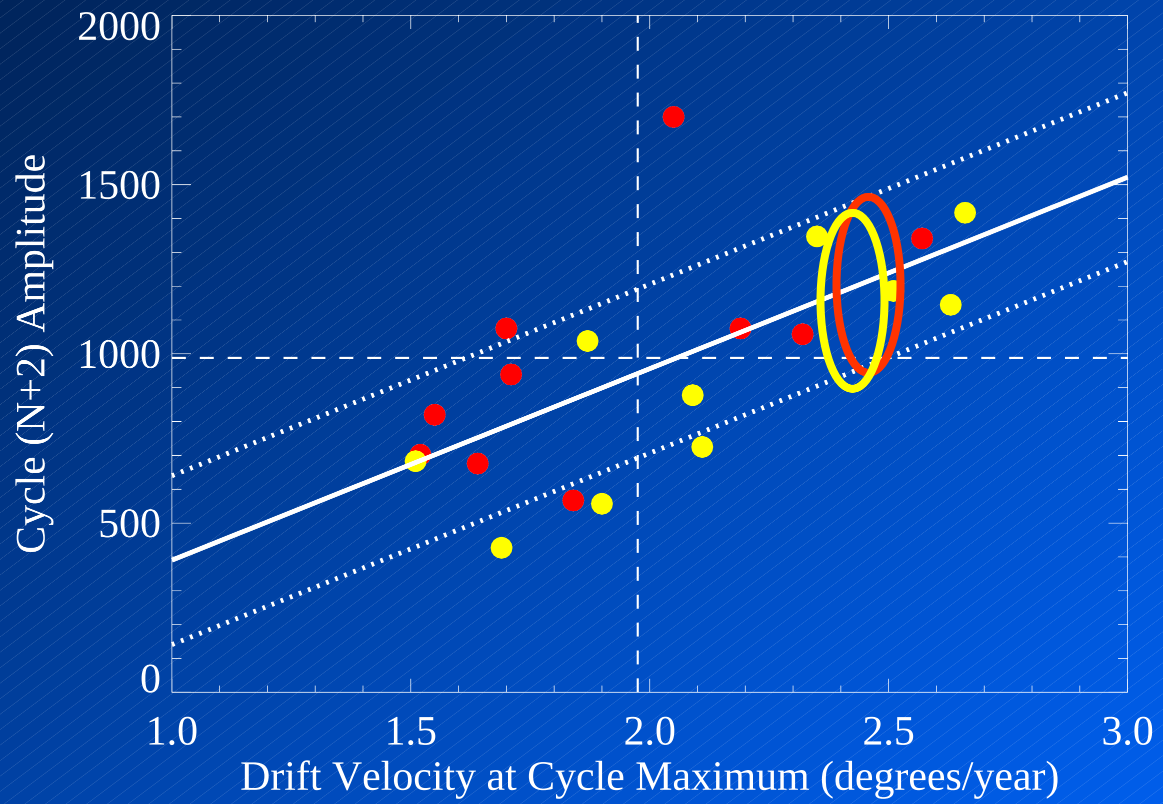
Drift Rate – Amplitude Correlations





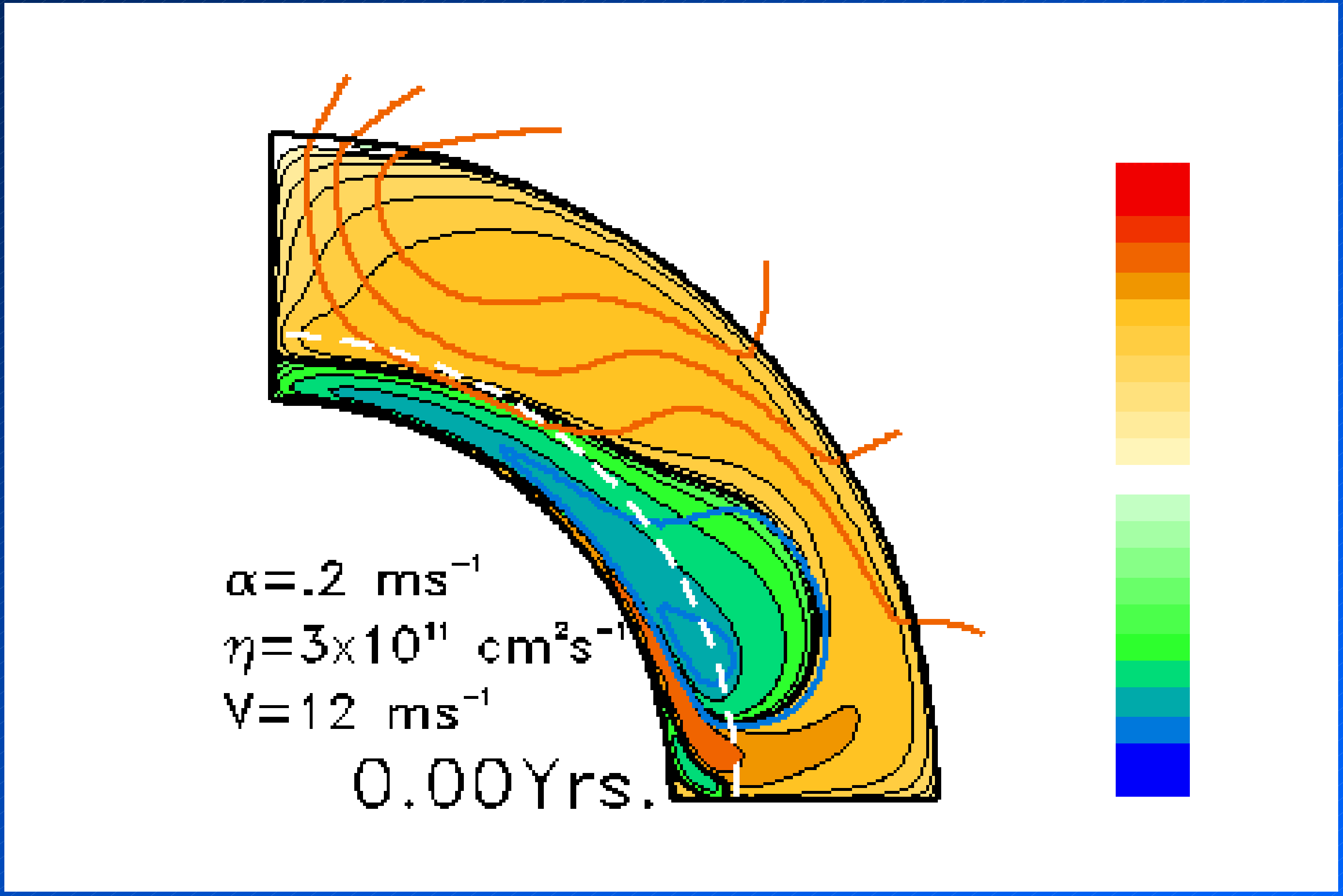
The drift velocity at cycle maximum is correlated to the cycle amplitude (Wang, Lean, & Sheeley, 2002) but a stronger, and more significant correlation is with the amplitude of the second following (N+2) cycle. This is a feature of dynamo models with fluctuating meridional flow (Charbonneau & Dikpati, 2000) and it offers a prediction for the amplitude of the next cycle.

Cycle 24 Prediction



The fast drift rates at the maximum of the last cycle (red oval – northern hemisphere, yellow oval – southern hemisphere) indicate a larger than average amplitude for the next cycle.

Dikpati & Charbonneau Dynamo



Conclusions

- The drift rate of the sunspot area centroid favors dynamo models with deep meridional flow
  1. *No poleward drift*
  2. *Slower drift rate at lower latitudes*
  3. *Anti-correlation between drift rate and cycle period*
  4. *Correlation between drift rate and N+2 cycle amplitude*
  5. *Flow rate of ~1.2 m/s consistent with helioseismology*

- The fast drift rates from the last cycle indicate that the next cycle will be a large amplitude cycle

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http://science.nasa.gov/ssl/pad/solar/papers.htm

Future Research Directions

•Use latitude drift measurements to get meridional flow vs time since 1874 to use as input to Dikpati's dynamo model – To what extent do variations in the meridional flow speed affect solar activity? (with Dikpati)

•Analyse short-term variations in drift rate and correlate with activity – Are the short term variations in the latitude position of the active latitudes correlated with solar activity levels? (with Wilson and Nandy)

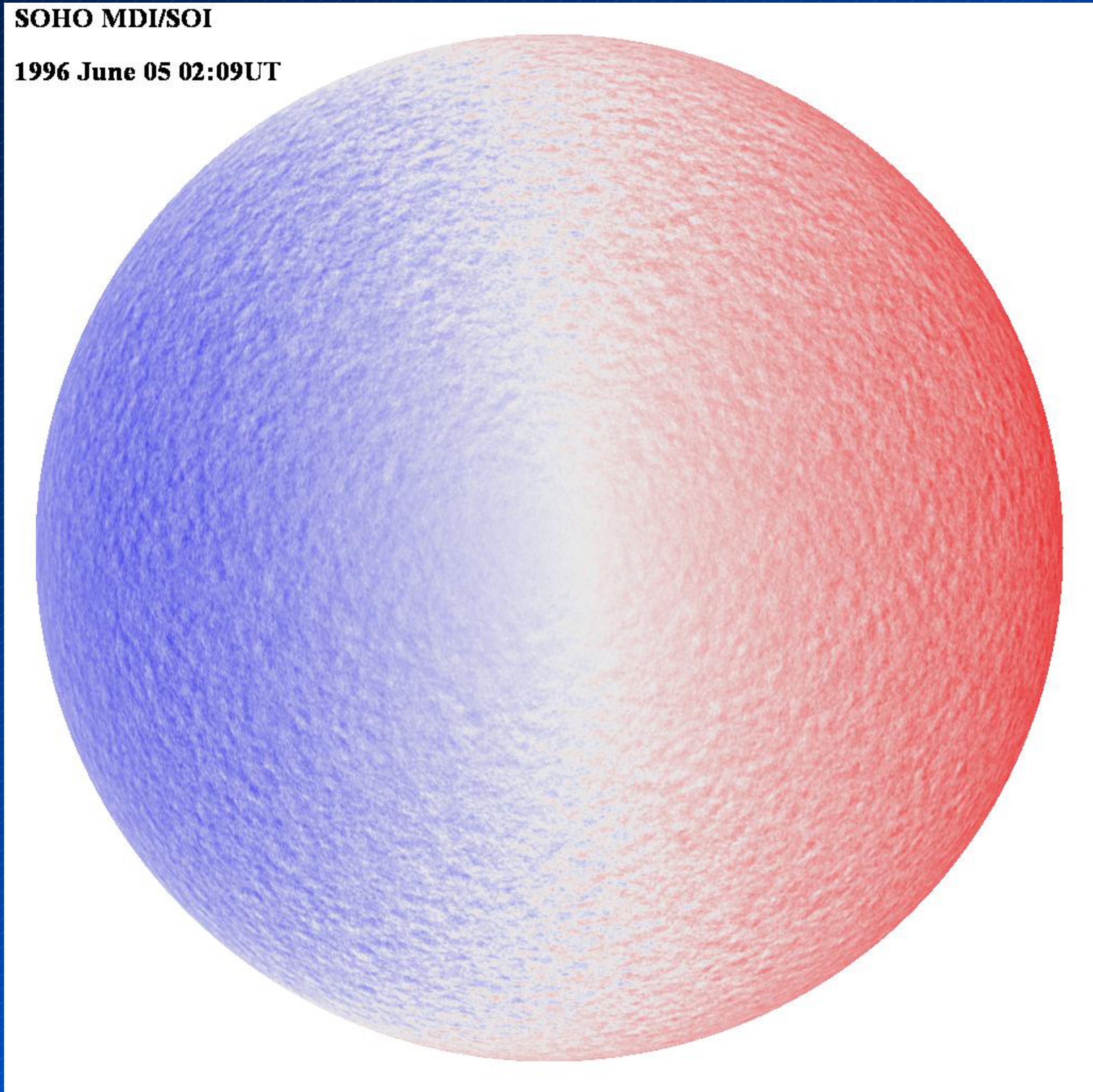
•Investigate details of magnetic flux transport in the photosphere – How does supergranulation transport flus across the surface? (with Prasad Choudhary and Narayankar)

Magnetic Flux Transport

AR 7978
Emergence

1996/07/02-1996/07/11
(Rotation 1911)
30x30 degree Area
Centered on:
Longitude 249
Latitude -11

Photospheric Flows

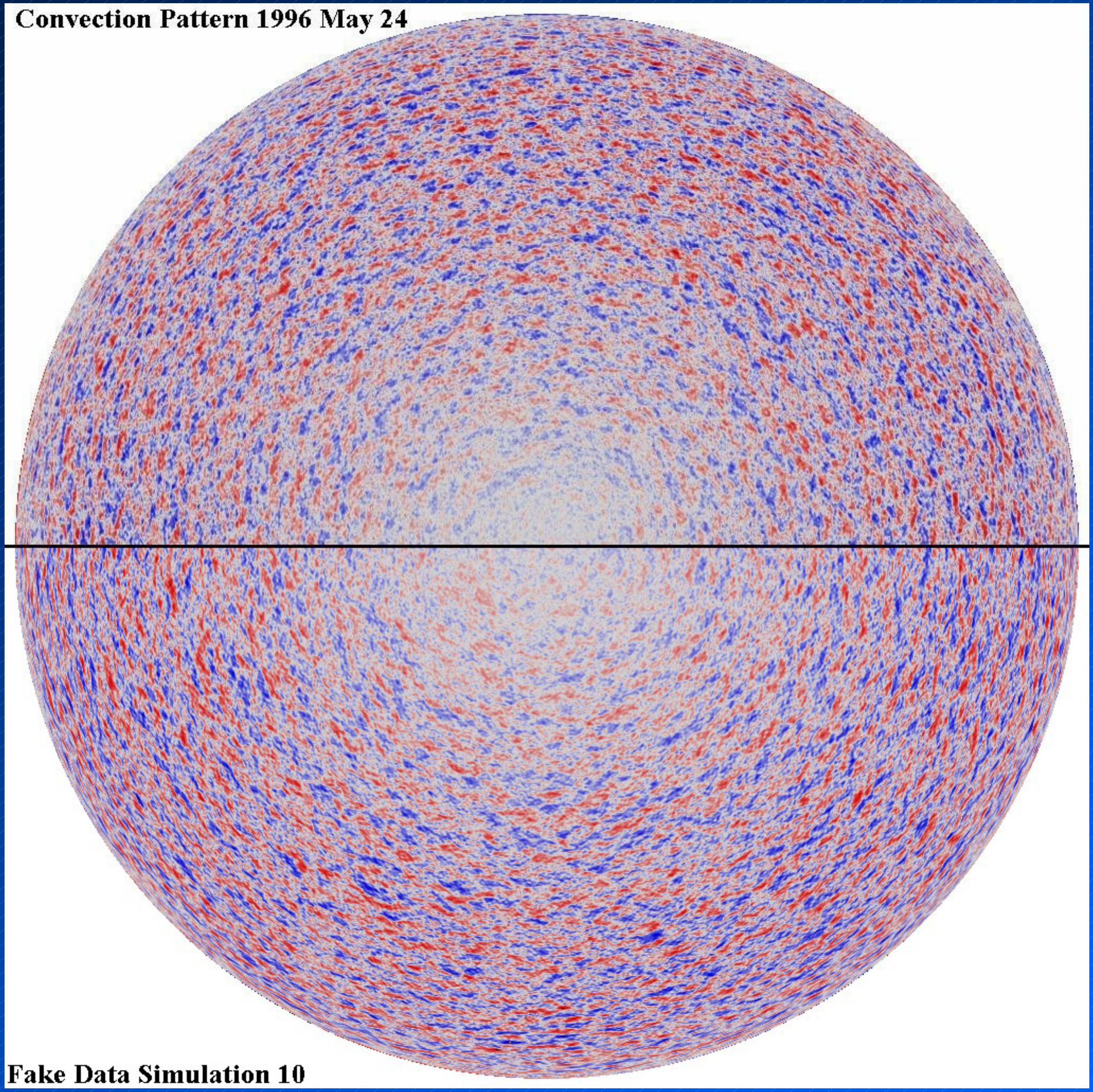


The surface flows are dominated by the basic rotation of the Sun and cellular flows but they also include differential rotation and the axisymmetric meridional flow.

These flows can be measured by direct Doppler imaging, feature tracking, and helioseismic inversions.

The flow characteristics can then be used in flux transport models.

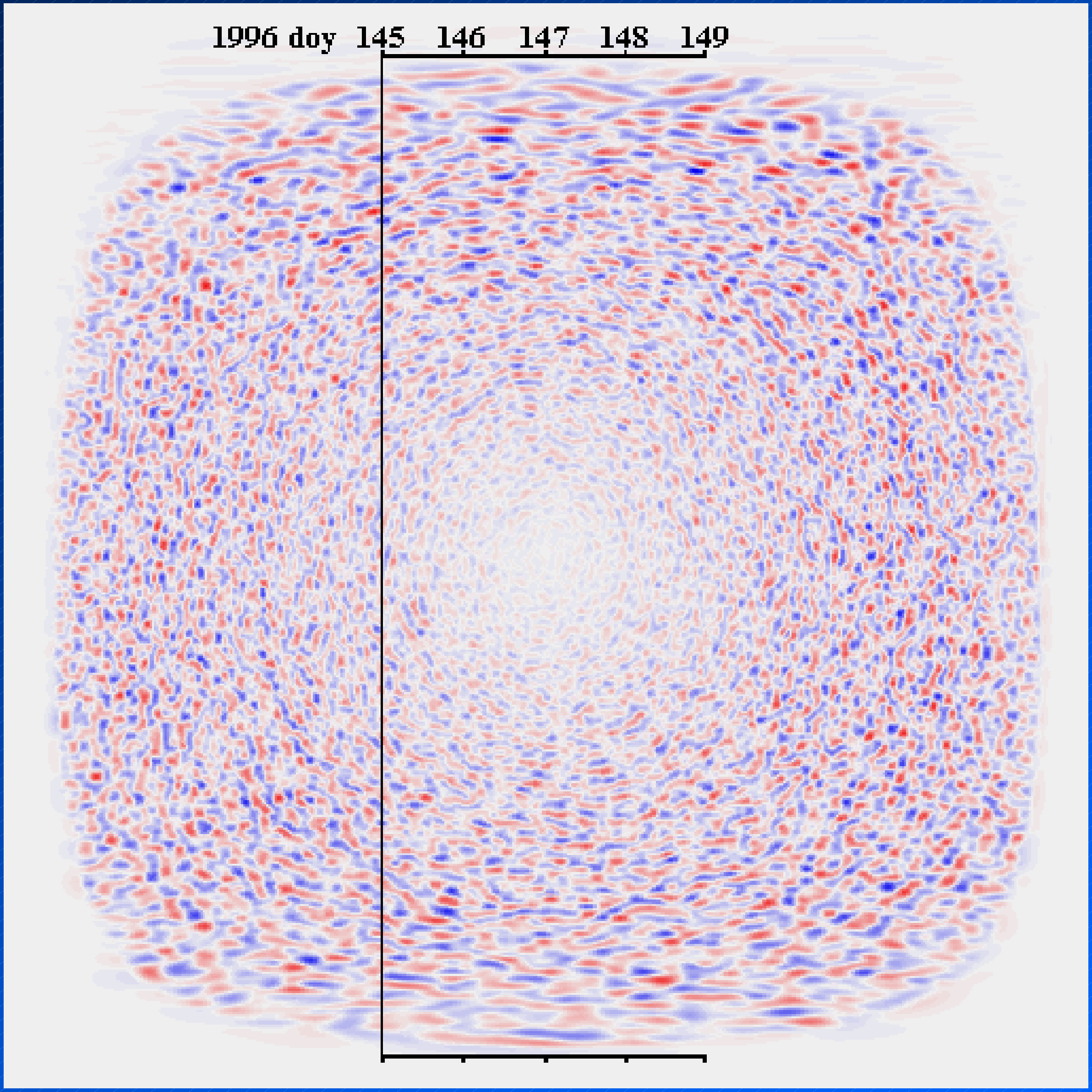
Supergranulation



Our Data simulations now match the appearance, spatial spectrum, and center to limb variation in the Doppler signal due to the cellular flows.

Final requirement is to match the temporal evolution of the pattern.

Supergranule Evolution



Photospheric Flow Maps